

Recent Results from STAR at RHIC

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Outline

- **Introduction**
- **Energy loss - QCD at work**
- **Charm production**
- **Bulk properties - ∂P_{QCD}**
- **Summary and Outlook**



Other STAR Physics Topics

- 1) Correlation and fluctuation
- 2) Ultra-peripheral collision
- 3) Resonance
- 4) Spin
- 5) Pentaquark search

<http://www.star.bnl.gov/STAR/>



//talk/2004/11UCSC/nxu_ucsc_11Nov04//

Study of Nuclear Collisions Like...

P.C. Sereno *et al.* **Science**, Nov. 13, 1298(1998).

(Spinosaurid)





Physics Goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

- direct photons, leptons
- “jets” and **heavy flavor**
- correlations

jets

- observed high p_T hadrons (at RHIC, $p_{T(\min)} > 3$ GeV/c)

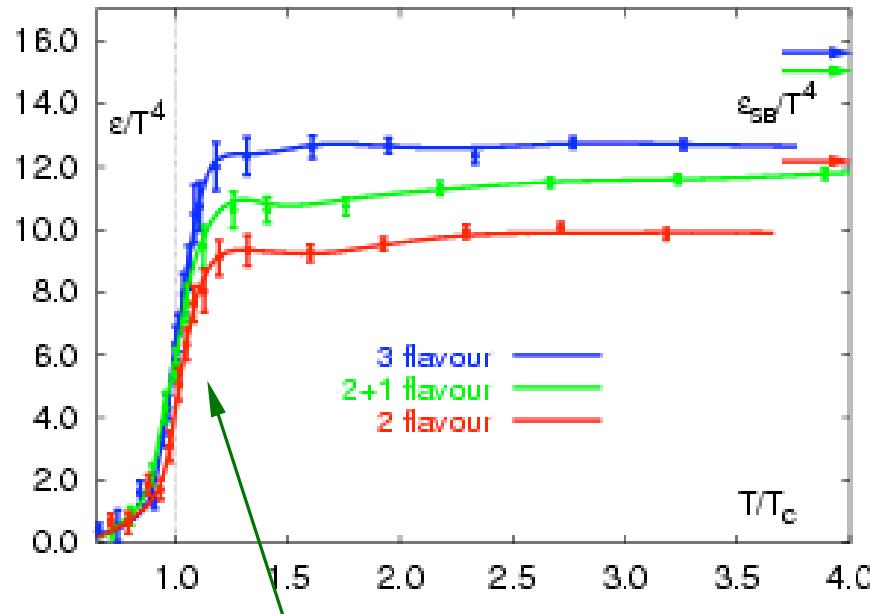
collectivity - collective motion of observed hadrons, not necessarily reached thermalization.

Bulk probes

- spectra, v_1 , v_2 ...
- partonic collectivity
- fluctuations



QCD on Lattice



Lattice calculations predict
 $T_c \sim 170$ MeV

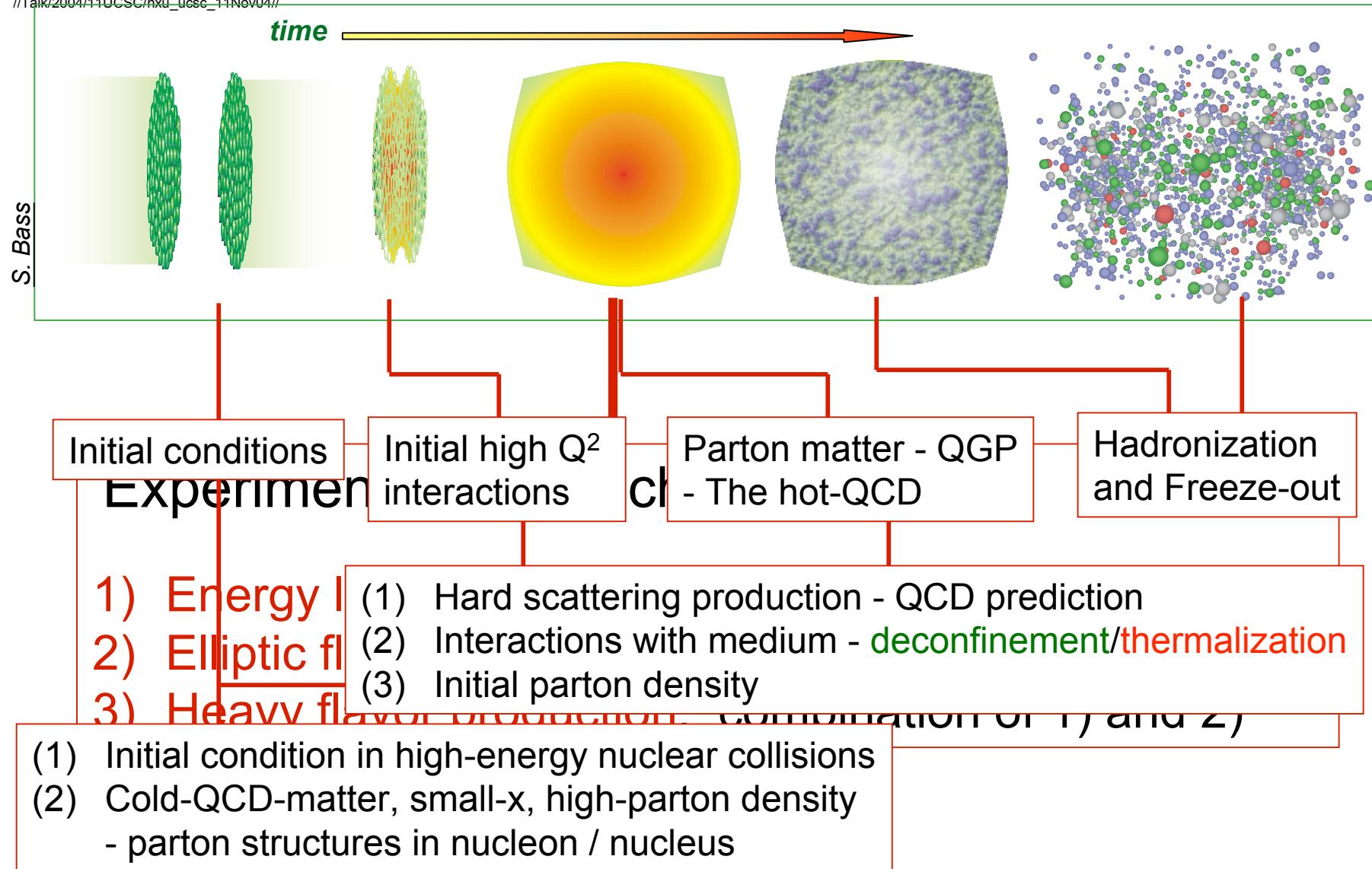
- 1) Large increase in \square
a fast cross cover !
- 2) Does not reach ideal,
non-interaction S. Boltzmann
limit !
 - \square many body interactions
 - \square Collective modes
 - \square Quasi-particles are necessary
- 3) $T_c \sim 170$ MeV robust!

Z. Fodor et al, *JHEP* 0203:014(02)
Z. Fodor et al, *hep-lat/0204001*
C.R. Allton et al, *hep-lat/0204010*
F. Karsch, *Nucl. Phys. A698*, 199c(02).



High-energy Nuclear Collisions

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High-energy Nuclear Collisions

Initial Condition

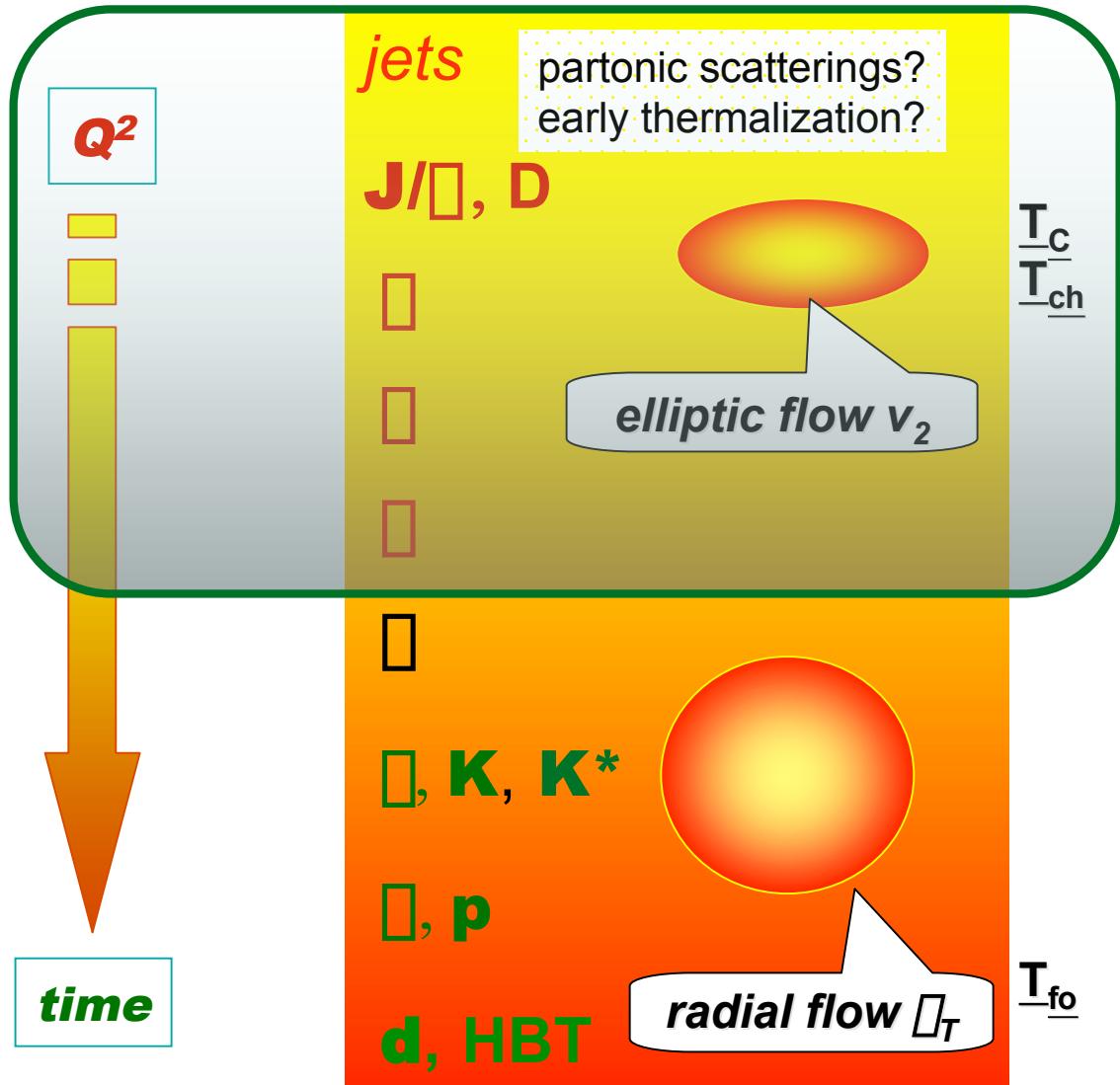
- initial scatterings
- baryon transfer
- E_T production
- parton dof

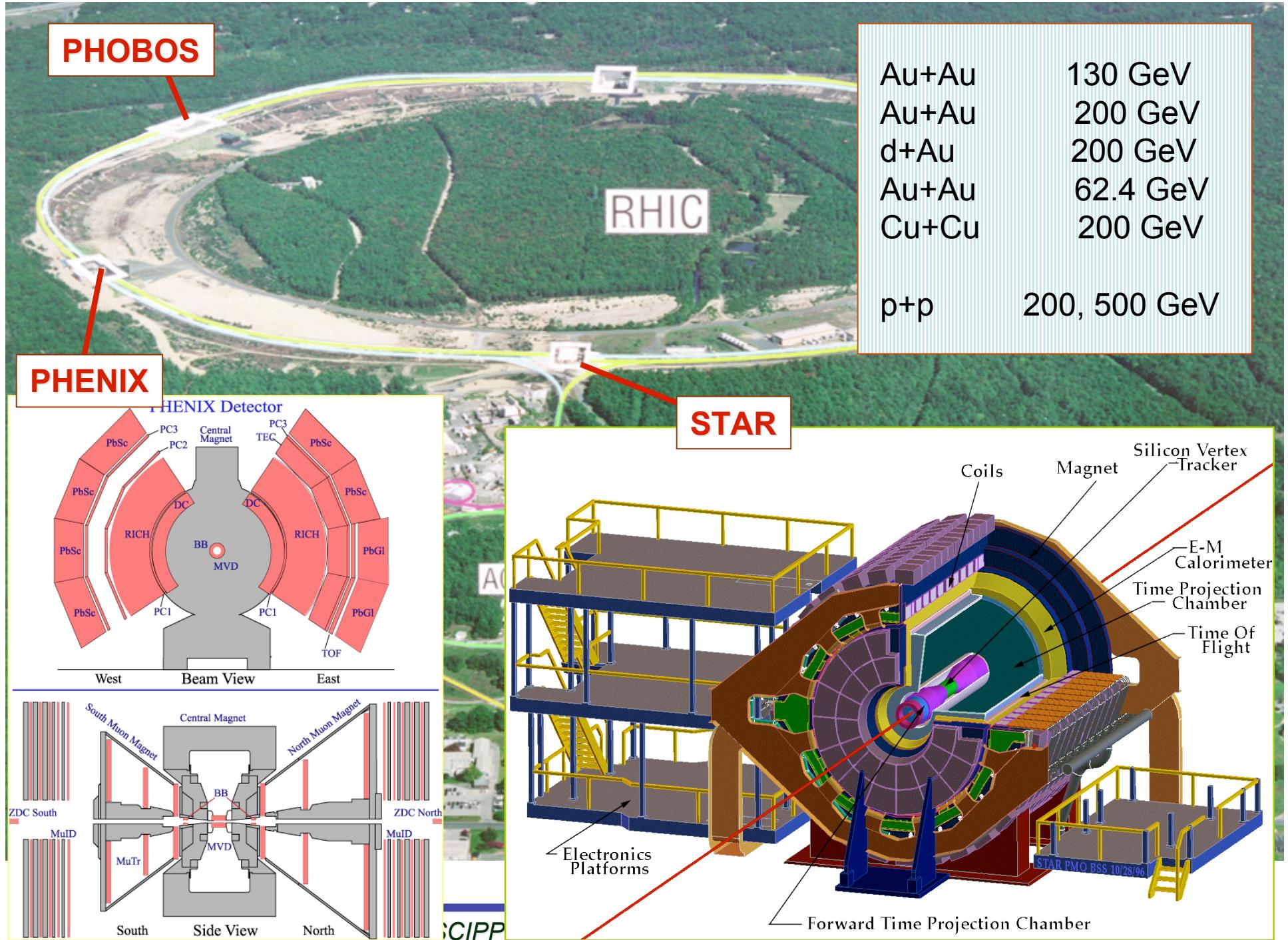
System Evolves

- parton interaction
- parton/hadron expansion

Bulk Freeze-out

- hadron dof
- interactions stop







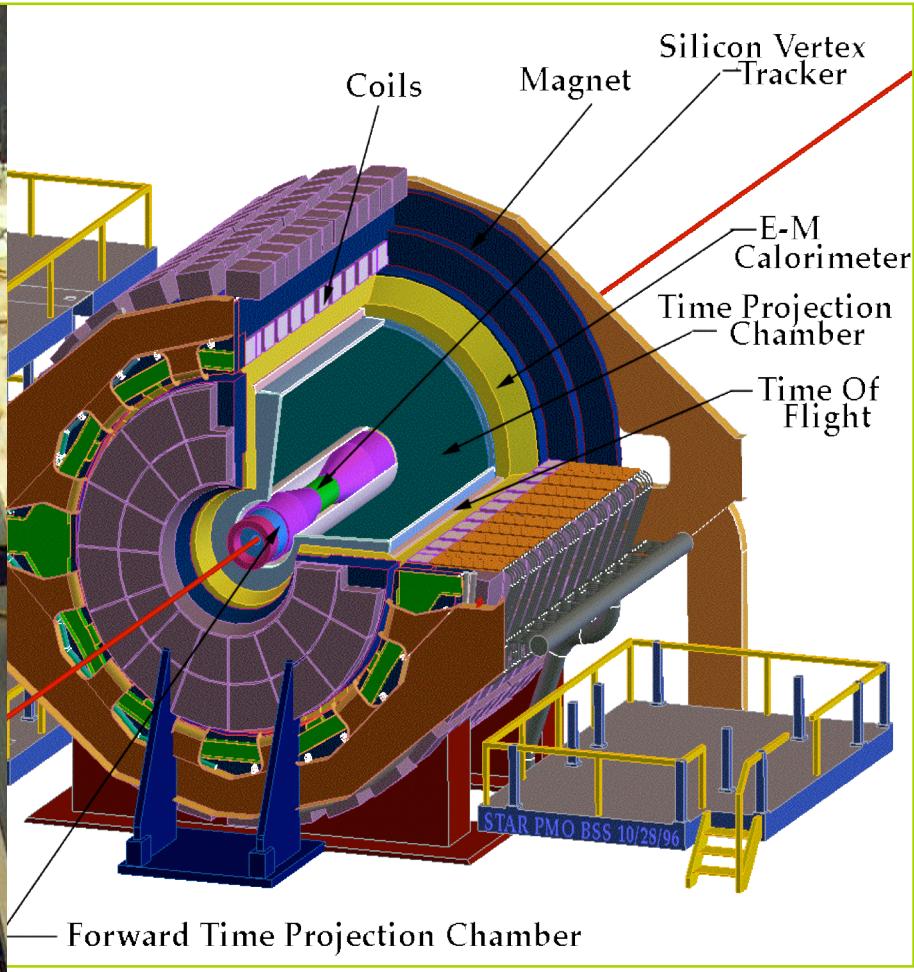
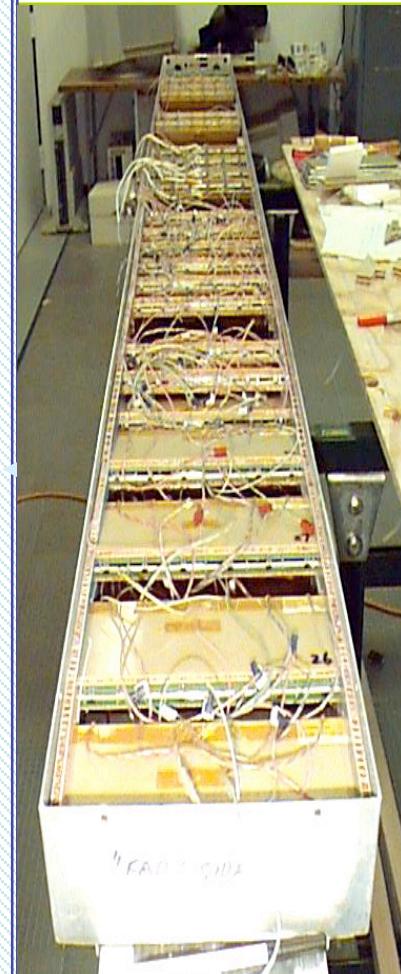
/Talk/2004/11/ICSC/avu_ncsc_11Nov04/

STAR: TPC & MRPC-TOF

A new technology -

Multi-gap Resistive Plate Chamber (MRPC), adopted from CERN-Alice

- A prototype detector of time-of-flight (**TOFr**) was installed in Run3
- One tray: ~ 0.3% of TPC coverage
- Intrinsic timing resolution: ~ 85 ps
- pion/kaon ID:**
 $p_T \sim 1.7 \text{ GeV}/c$
- proton ID:**
 $p_T \sim 3 \text{ GeV}/c$



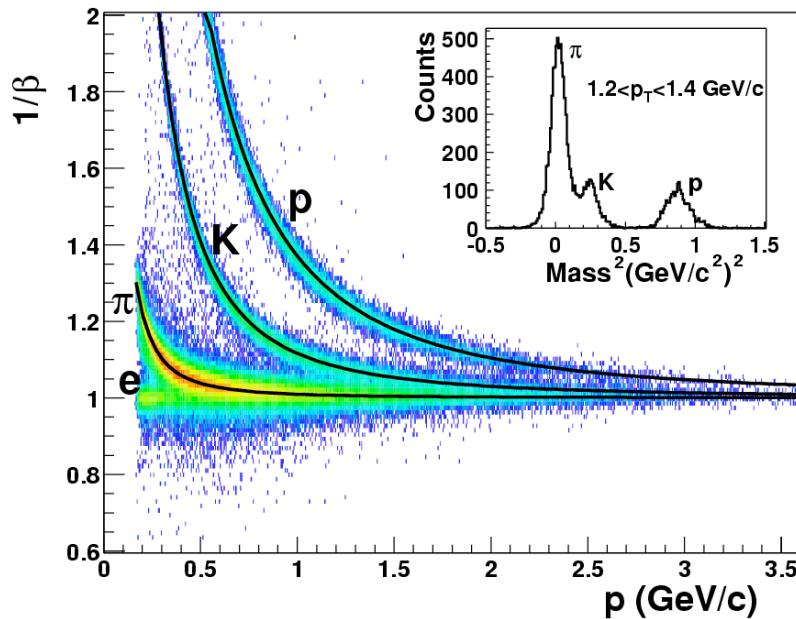
TPC dE/dx PID:

pion/kaon: $p_T \sim 0.6 \text{ GeV}/c$; proton $p_T \sim 1.2 \text{ GeV}/c$

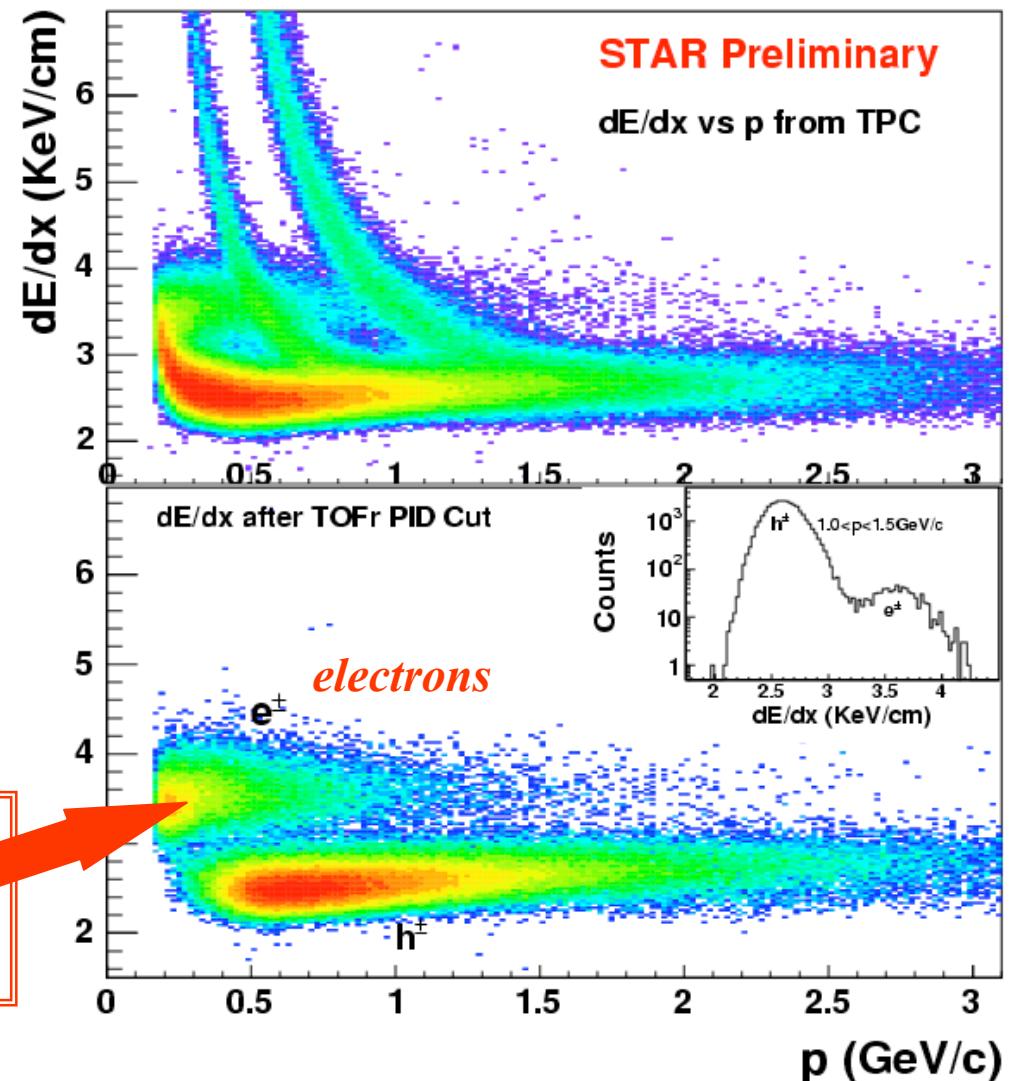


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STAR TOFr PID



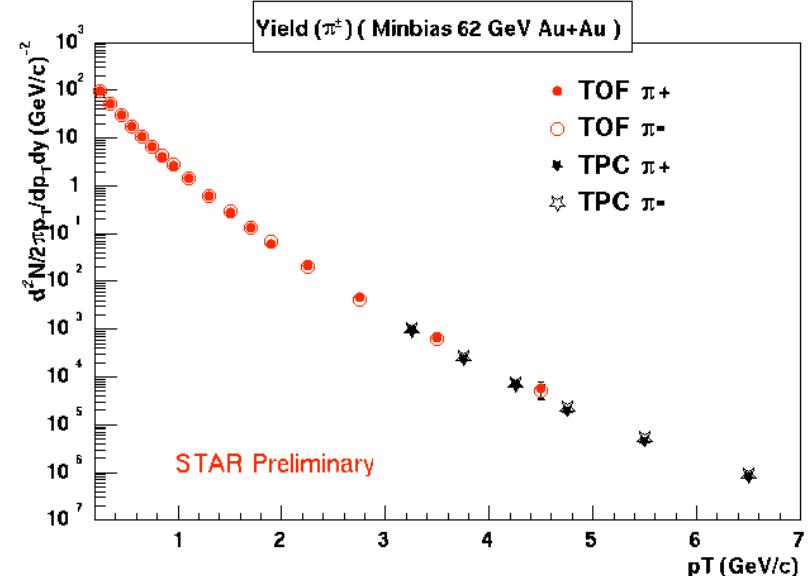
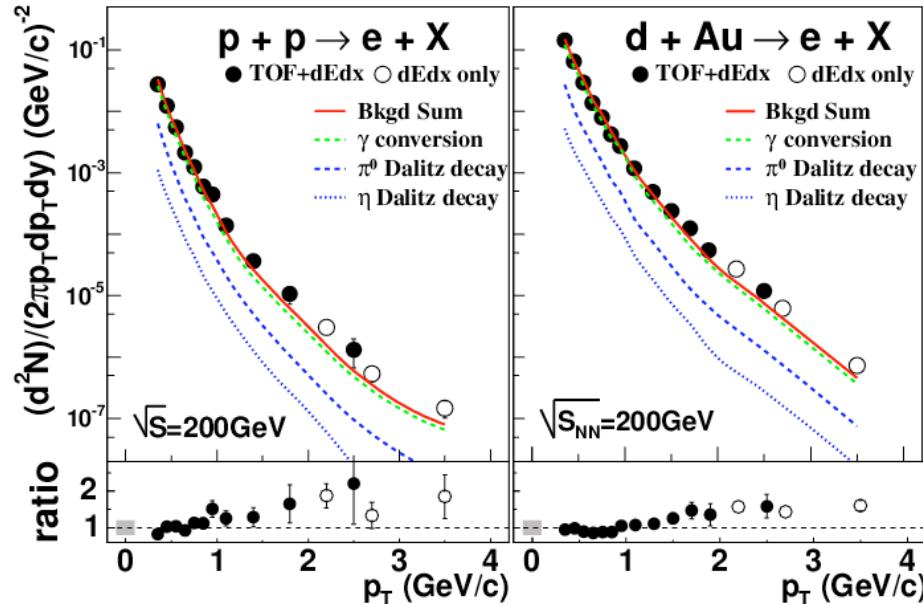
Hadron identification:
STAR Collaboration, [nucl-ex/0309012](https://arxiv.org/abs/nucl-ex/0309012)



Electron identification:
TOFr $|1/\beta - 1| < 0.03$
TPC dE/dx electrons!!!

Electron, pion spectra

STAR Preliminary



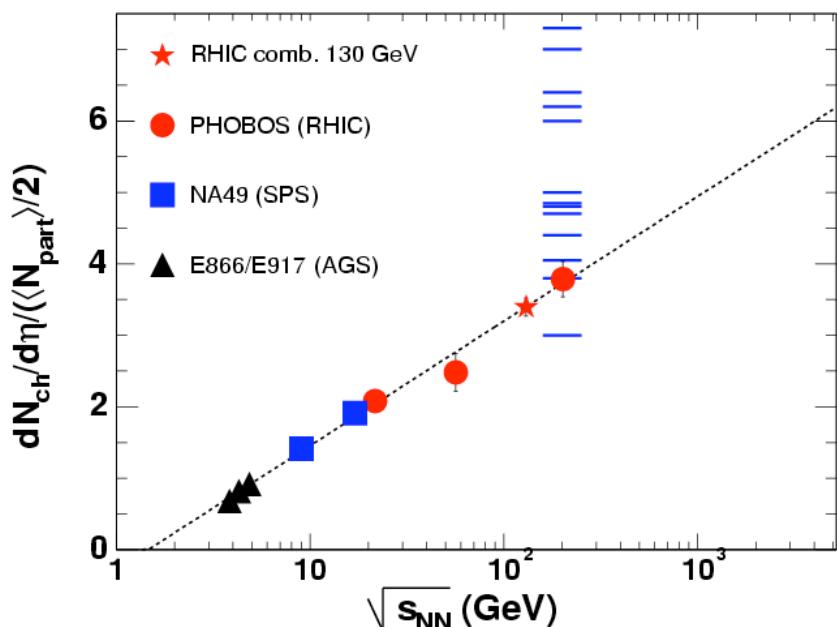
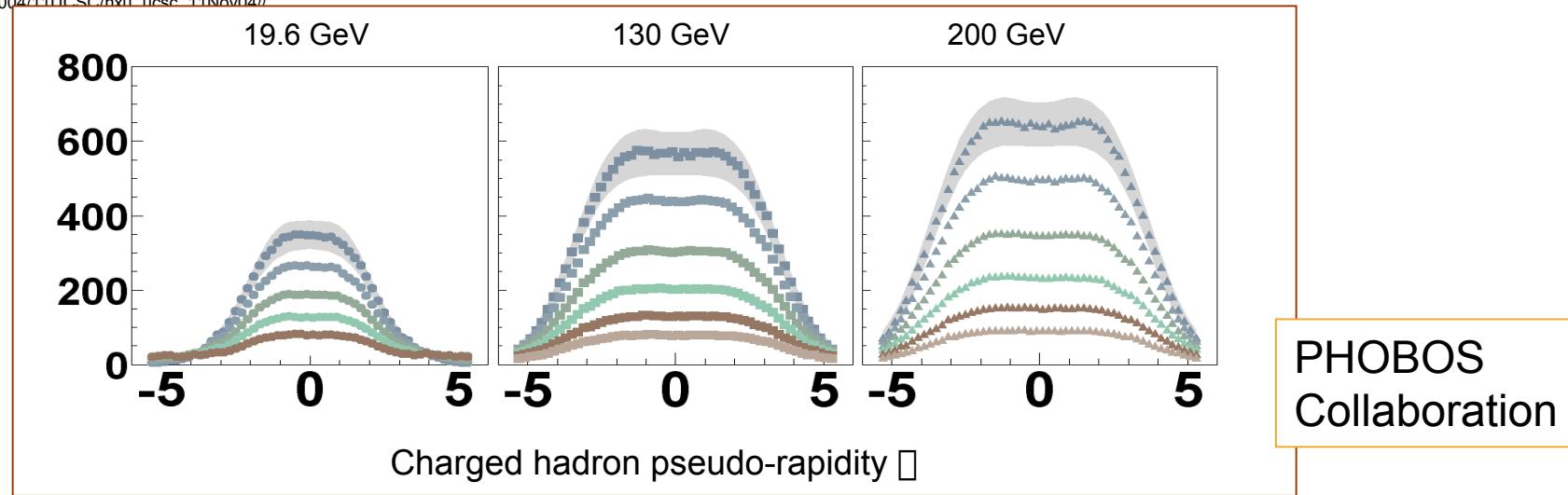
- 1) An increasing excess found at higher p_T region, $p_T > 1.0 \text{ GeV}/c$,
→ Expected contribution of semi-leptonic decays from heavy flavor hadrons
- 2) Pion identification up to $p_T \sim 7 \text{ GeV}/c$

STAR: [nucl-ex/0407006](#)



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Global: Charge hadron density



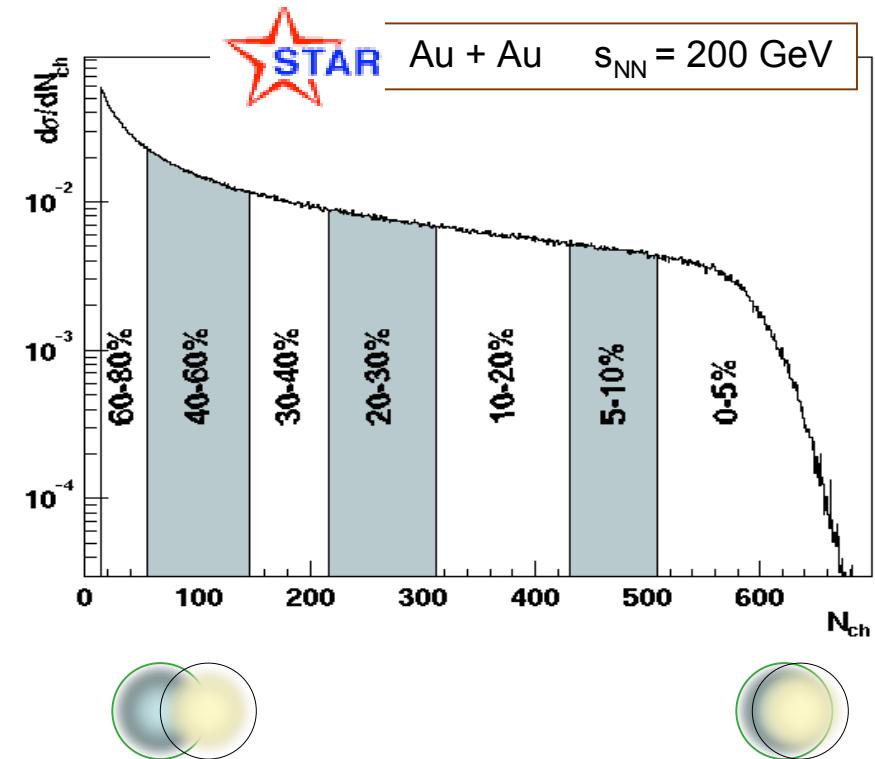
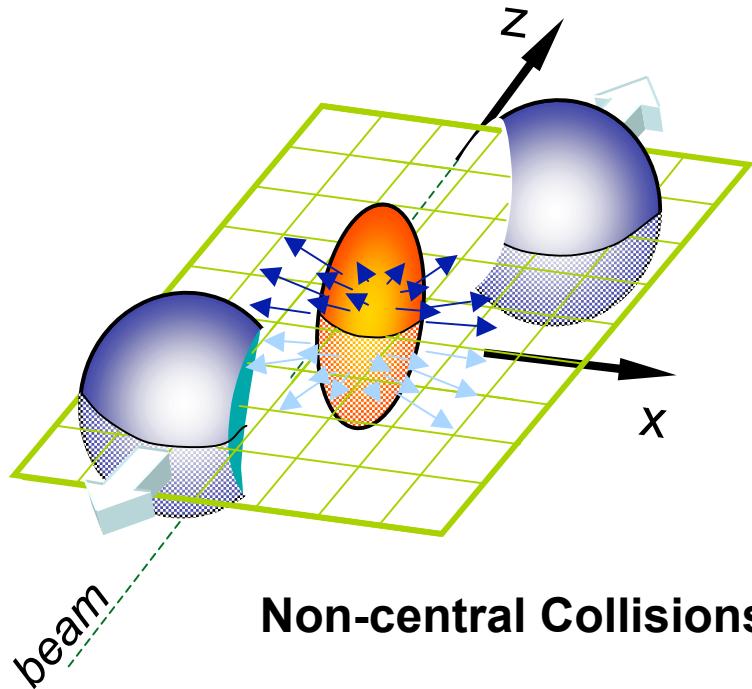
- 1) High number of N_{ch} indicates initial high density;
- 2) Mid-y, $N_{ch} \propto N_{part} \Rightarrow$ nuclear collisions are not incoherent;

Important for high density and thermalization.

PRL 85, 3100 (00); 91, 052303 (03); 88, 22302 (02), 91, 052303 (03)



Collision Geometry



Number of participants: number of incoming nucleons in the overlap region

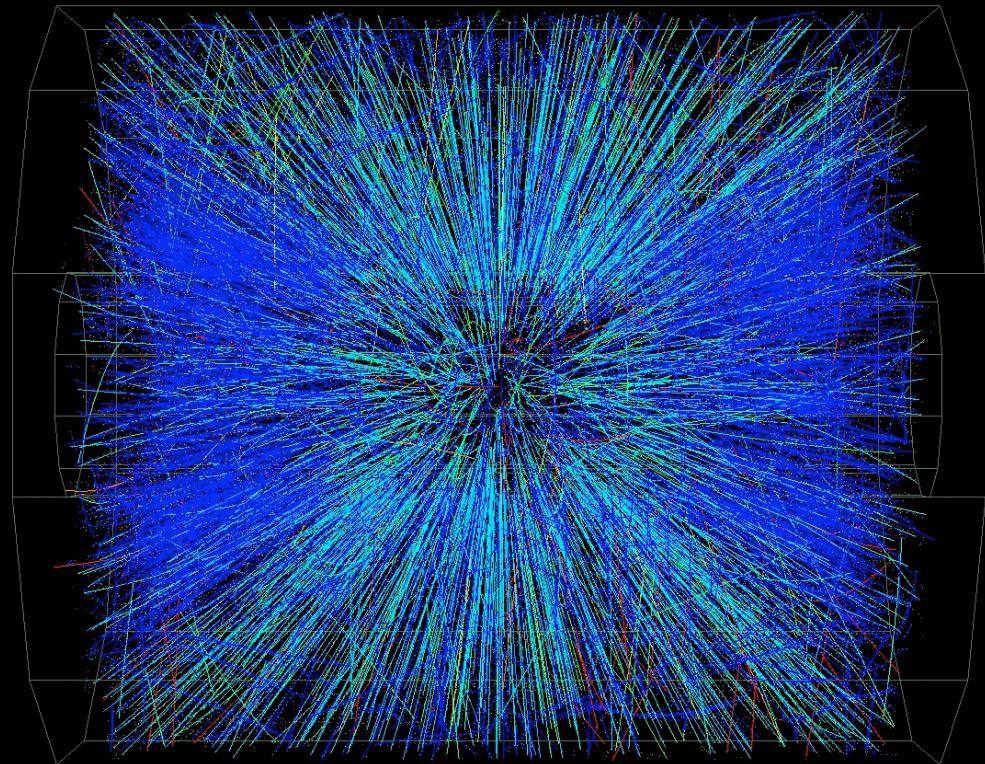
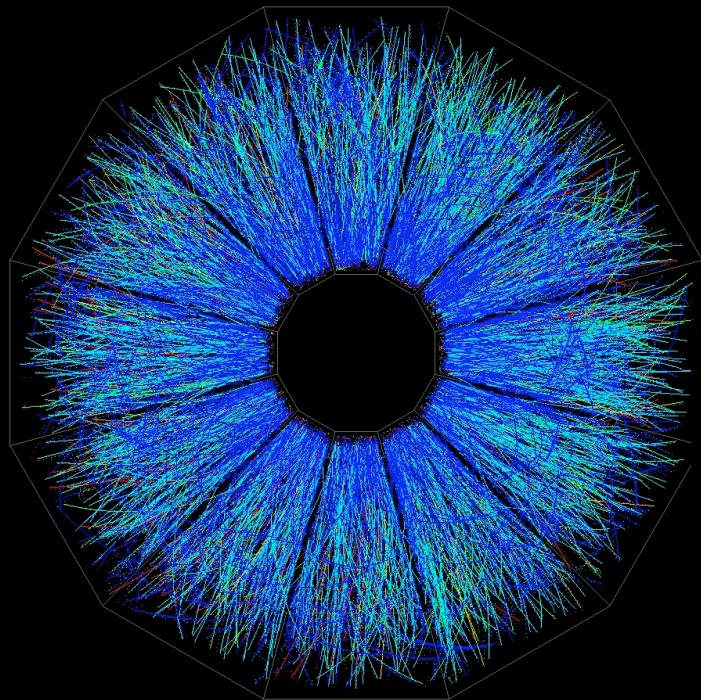
Number of binary collisions: number of inelastic nucleon-nucleon collisions

Charged particle multiplicity collision centrality

Reaction plane: x-z plane

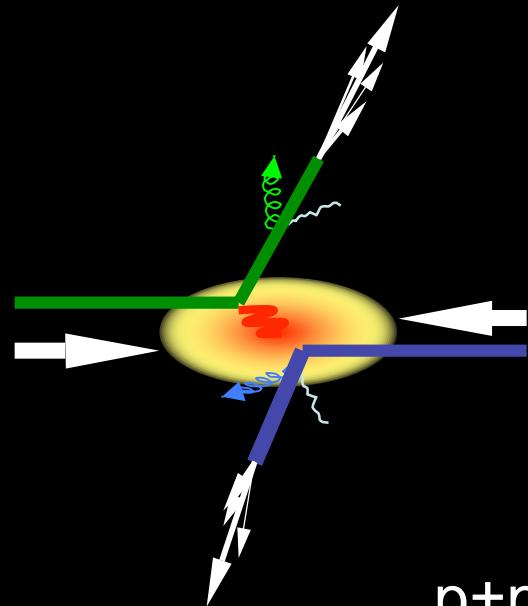
Au + Au Collisions at RHIC

Central Event

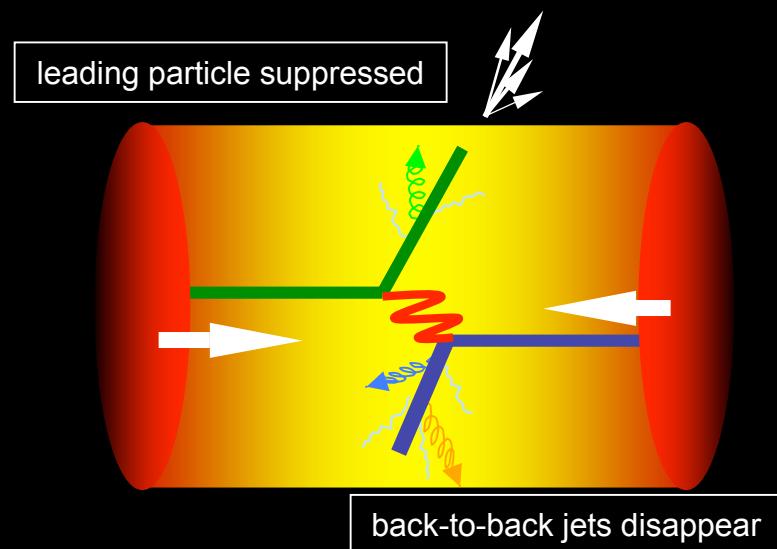


(real-time Level 3)

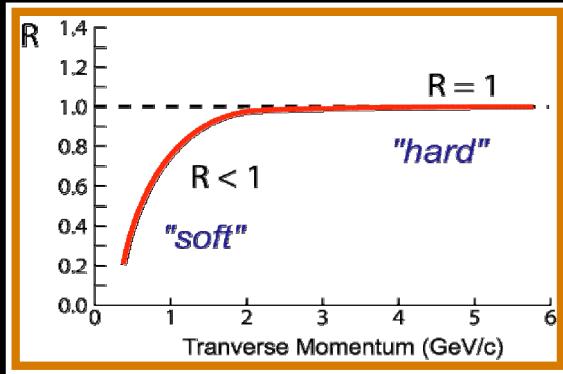
Energy Loss in A+A Collisions



$p+p$



$Au + Au$



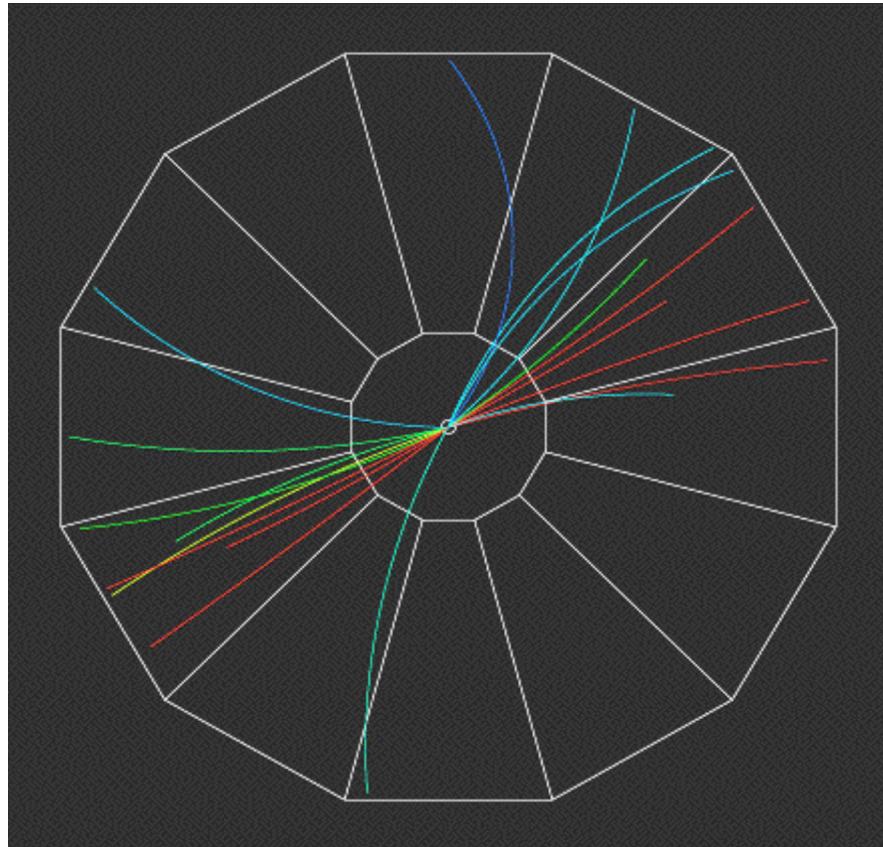
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2 N^{AA} / dp_T d\Omega}{d^2 \Omega^{NN} / dp_T d\Omega}$$

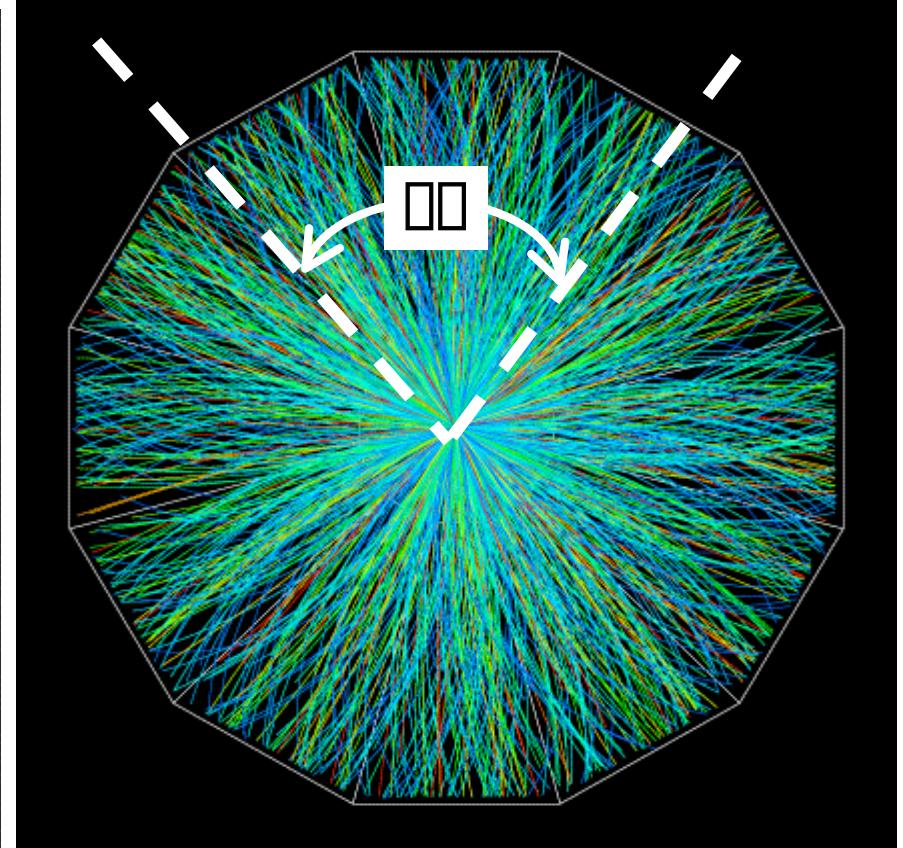


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'Jets' Observation at RHIC



p+p collisions at RHIC
Jet like events observed

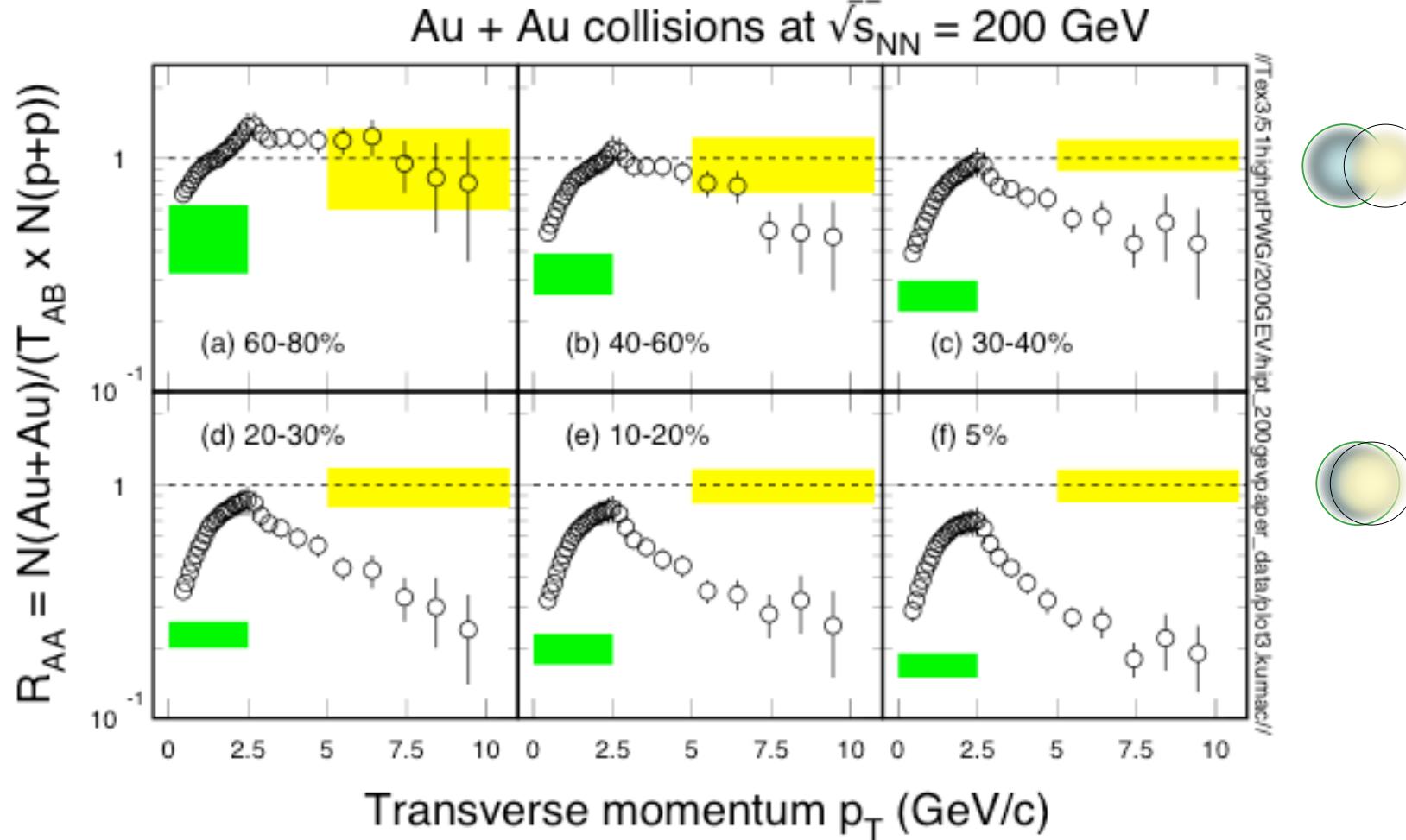


Au+Au collisions at RHIC
Jets effects?



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Hadron Suppression at RHIC



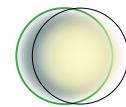
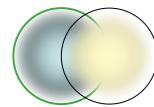
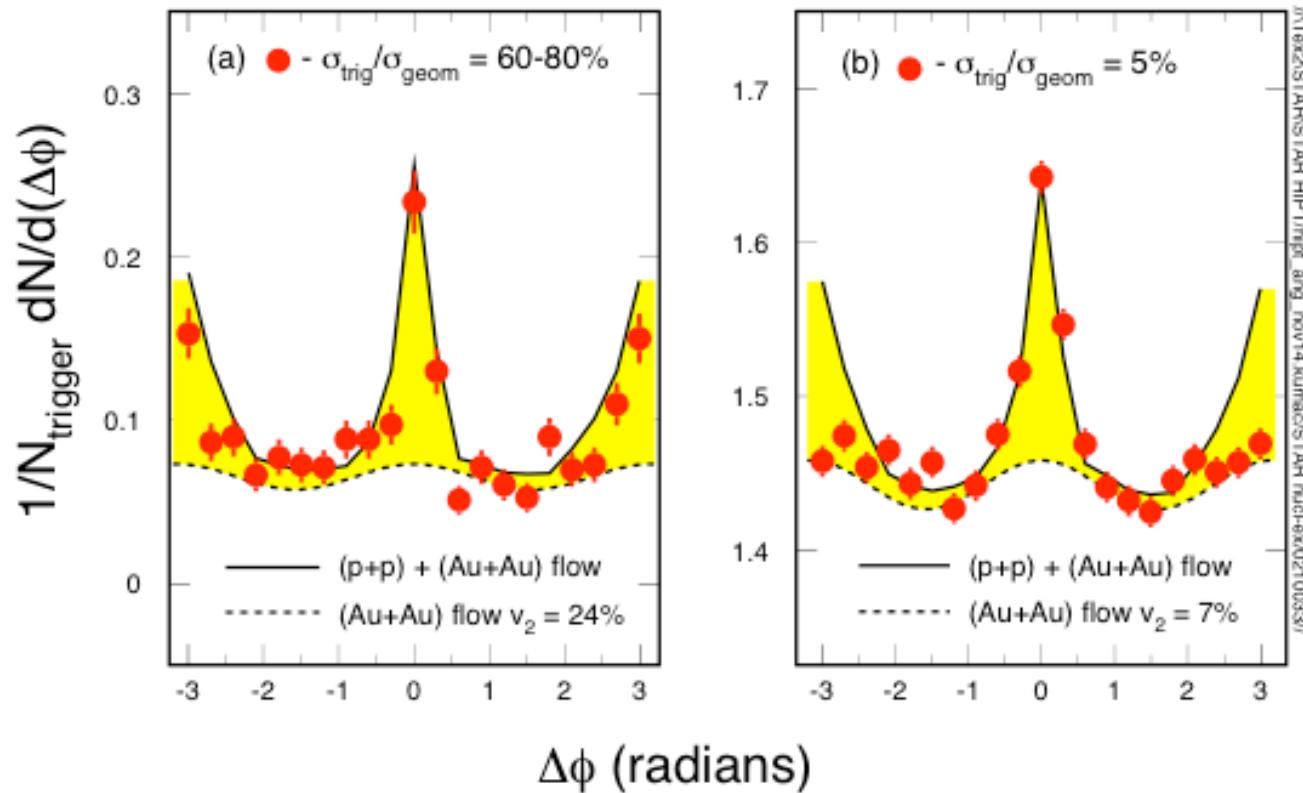
Hadron suppression in more central Au+Au collisions!



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Jet angular correlations

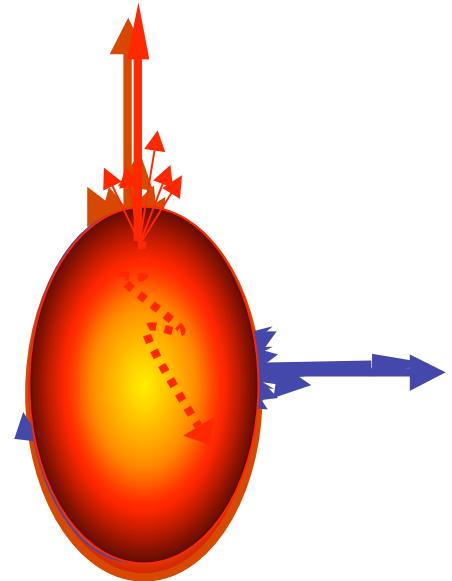
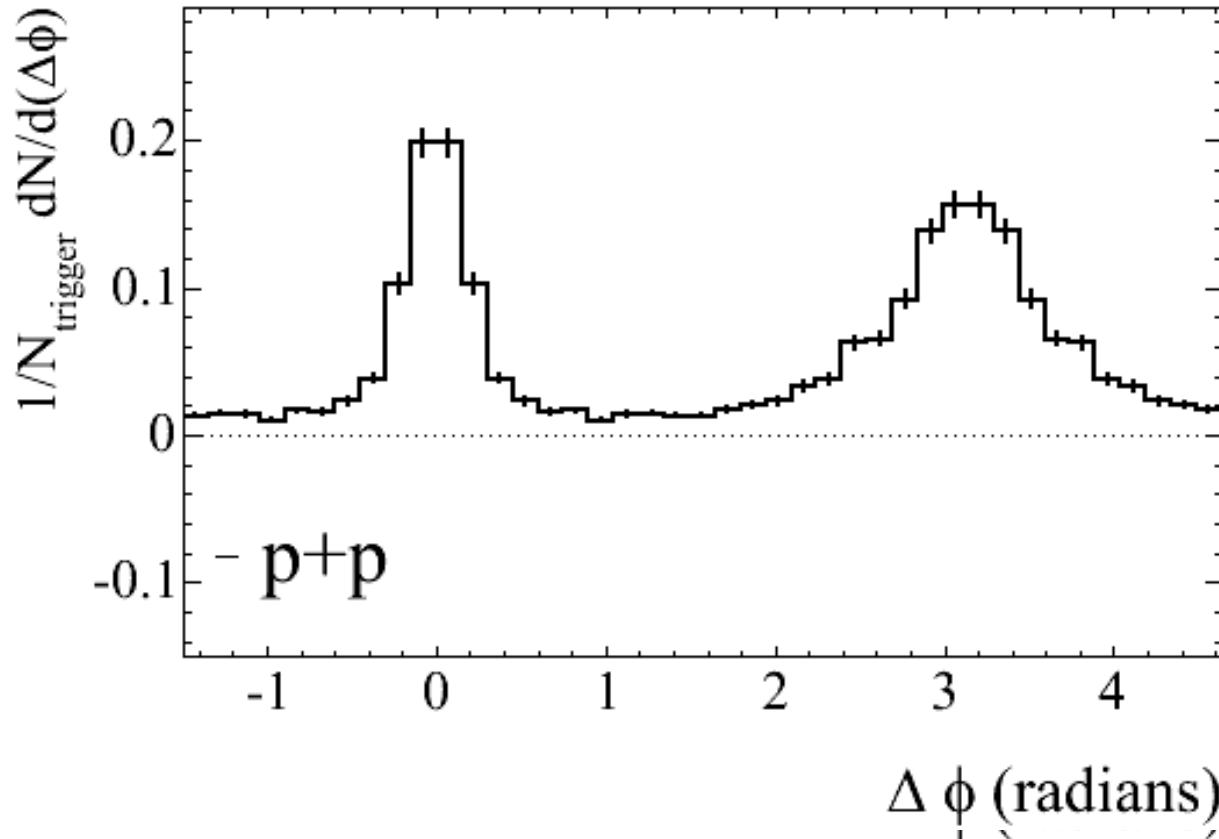
$^{197}\text{Au} + ^{197}\text{Au}$ at RHIC ($\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$)





Azimuthal Angular Dependence

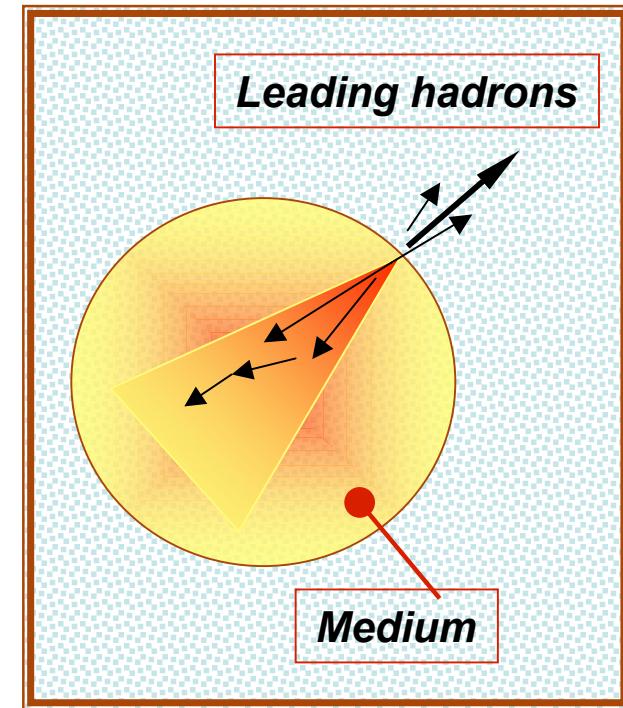
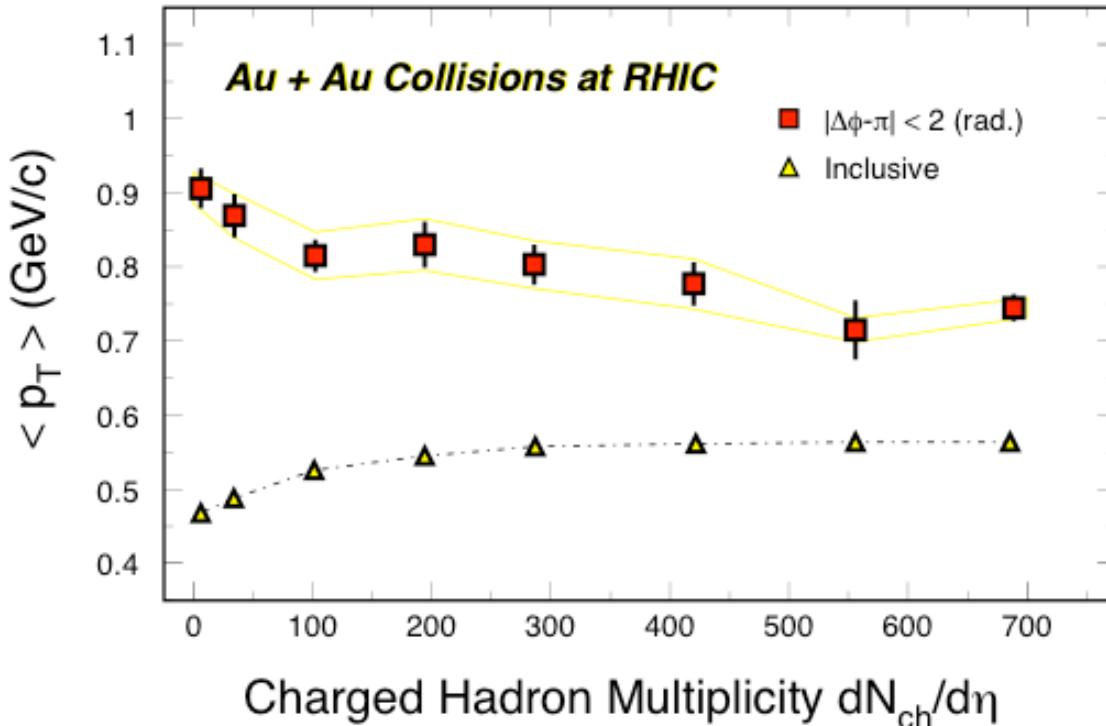
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- Away-side suppression: larger for out-of-plane than in-plane!
- The energy loss depends on the distance traveled through the medium!
- Geometry of the dense medium imprints itself on correlations!



Energy Loss and Equilibrium



In Au +Au collision at RHIC:

- Suppression at the intermediate p_T region - energy loss
- The energy loss leads to progressive equilibrium in Au+Au collisions

STAR: *nucl-ex/0404010*



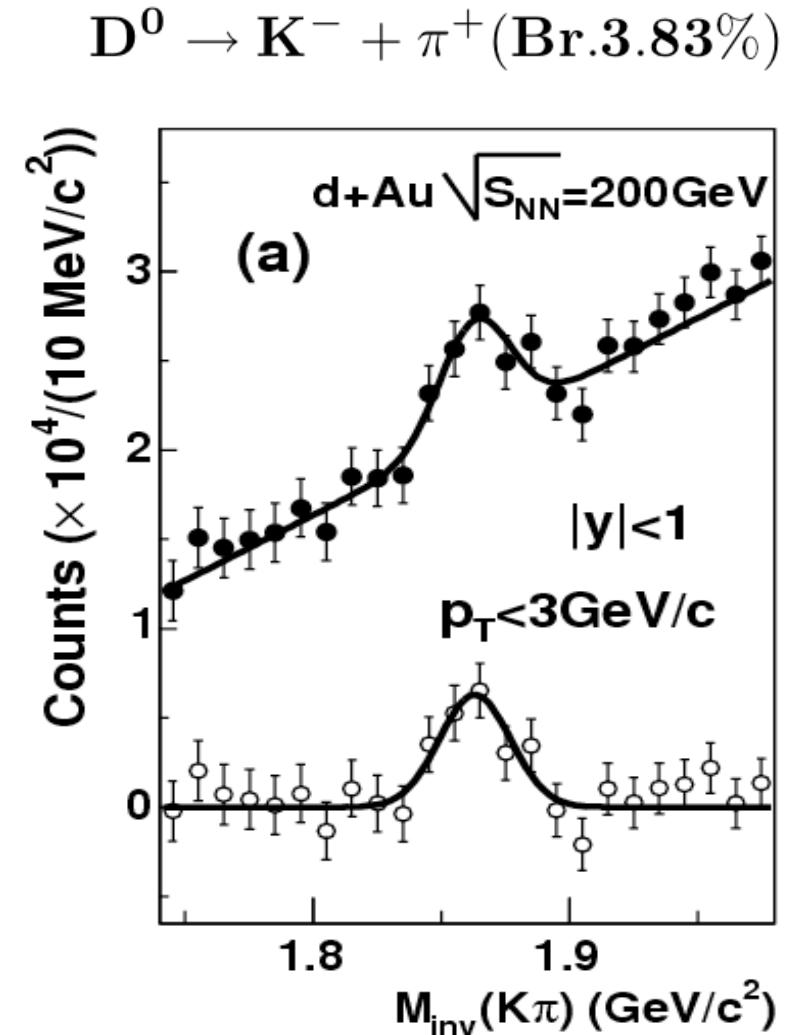
Direct reconstruction of D⁰

- 1) Heavy flavor production sensitive to medium effect - energy loss and collective effect;
- 2) Large cross section - parton thermalization and J/ψ
- 3) Better pQCD predictions(?)

First direct open charm reconstruction at RHIC!

Event mixing method:

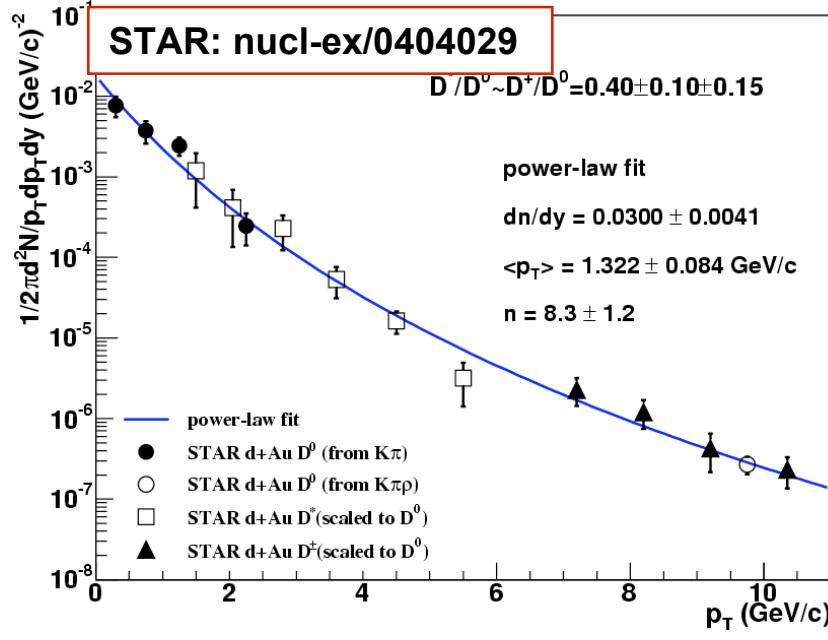
C. Adler et al., *Phys. Rev. C66*, 061901(R)(2002)
H. Zhang, *J. Phys. G30*, S577(2004)



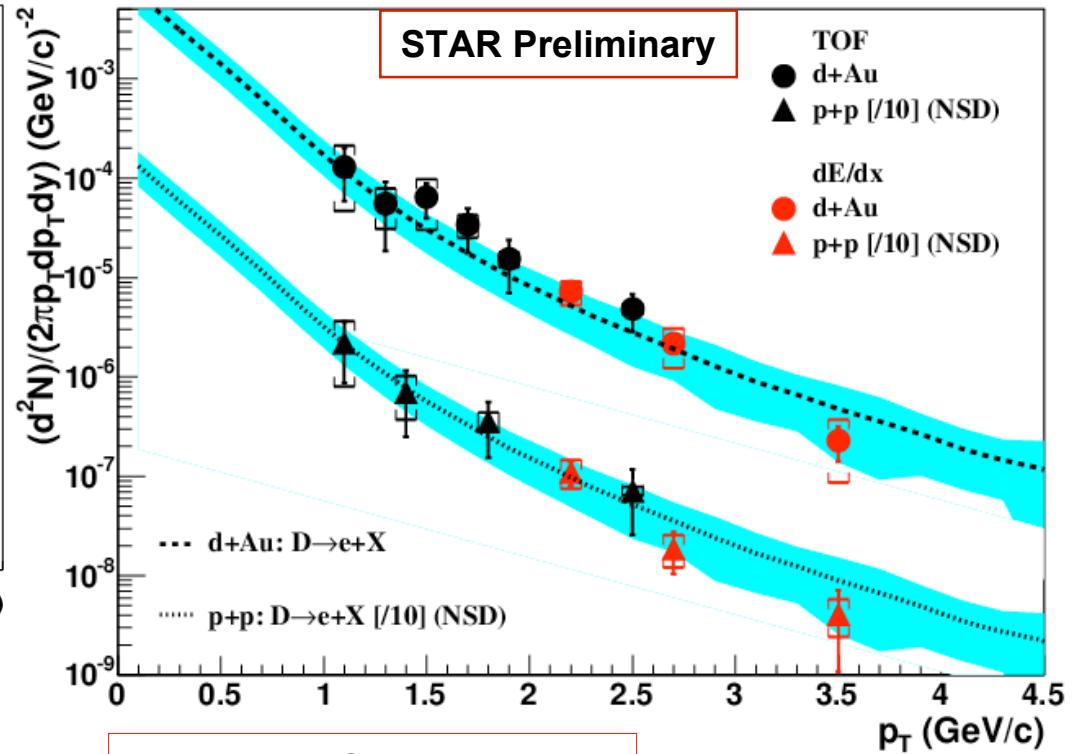


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Consistent in D measurements



Directly reconstructed D mesons

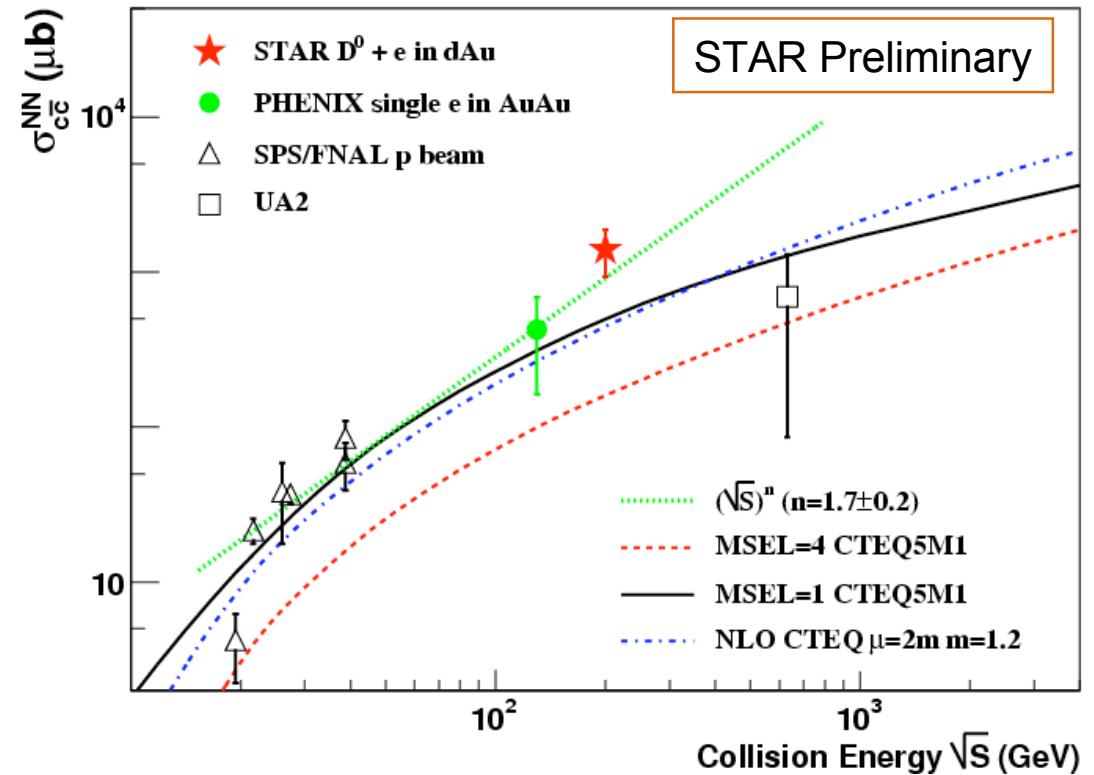


Electrons from D decay

D and electron spectra are consistent!

Charm production cross-section

- 1) NLO pQCD calculations under-predict the ccbar production cross section at RHIC
- 2) Power law for ccbar production cross section from SPS to RHIC:
 $n \sim 2$
(n~0.5 for charged hadrons)
- 3) Large uncertainties in total cross section due to rapidity width, model dependent(?).





Charm production at RHIC

- 1) Open charm yields measured in both 200GeV p+p and d+Au collisions. No evidence of deviation from binary collision scaling in d+Au collisions

$$\bar{\Lambda}_{c\bar{c}}^{\text{total}} = 700 \pm 1200 (\mu\text{b})$$

- 2) Perturbative calculations under predicted both yields and spectrum shape. Hadronization process not under control
 - 1) Study open charm v_2 and J/ψ yields to address thermalization issues at RHIC.



Pressure, Flow, ...

$$\boxed{dU} = dU + pdV$$

\square - entropy; p – pressure; U – energy; V – volume
 $\square = k_B T$, thermal energy per dof

In high-energy nuclear collisions, *interaction* among constituents and *density distribution* will lead to:

pressure gradient* \square *collective flow

- \square number of degrees of freedom (dof)
- \square Equation of State (EOS)
- \square No thermalization needed – pressure gradient only depends on the ***density gradient and interactions***.
- \square Space-time-momentum correlations!



Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\Omega} = \frac{1}{2\Omega} \frac{dN}{p_t dp_t dy} \left[1 + \sum_{i=1}^{\Omega} 2v_i \cos(i\Omega) \right]$$
$$p_t = \sqrt{p_x^2 + p_y^2}, \quad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass:

- Directed flow (v_1) – early
- Elliptic flow (v_2) – early
- Radial flow – integrated over whole evolution

Note on collectivity:

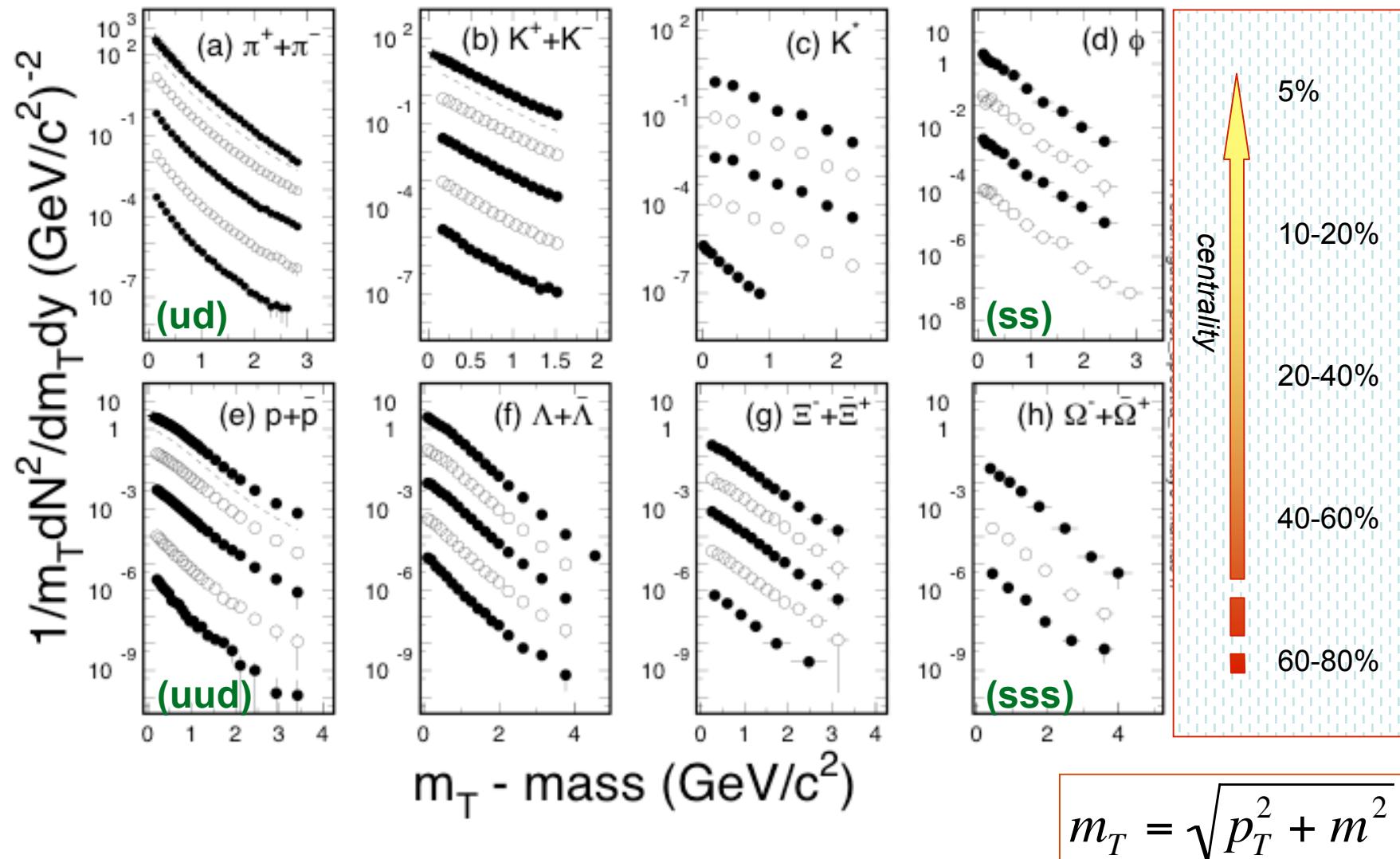
- 1) Effect of collectivity is accumulative – final effect is the sum of all processes.
- 2) Thermalization is not needed to develop collectivity - pressure gradient depends on **density gradient** and **interactions**.



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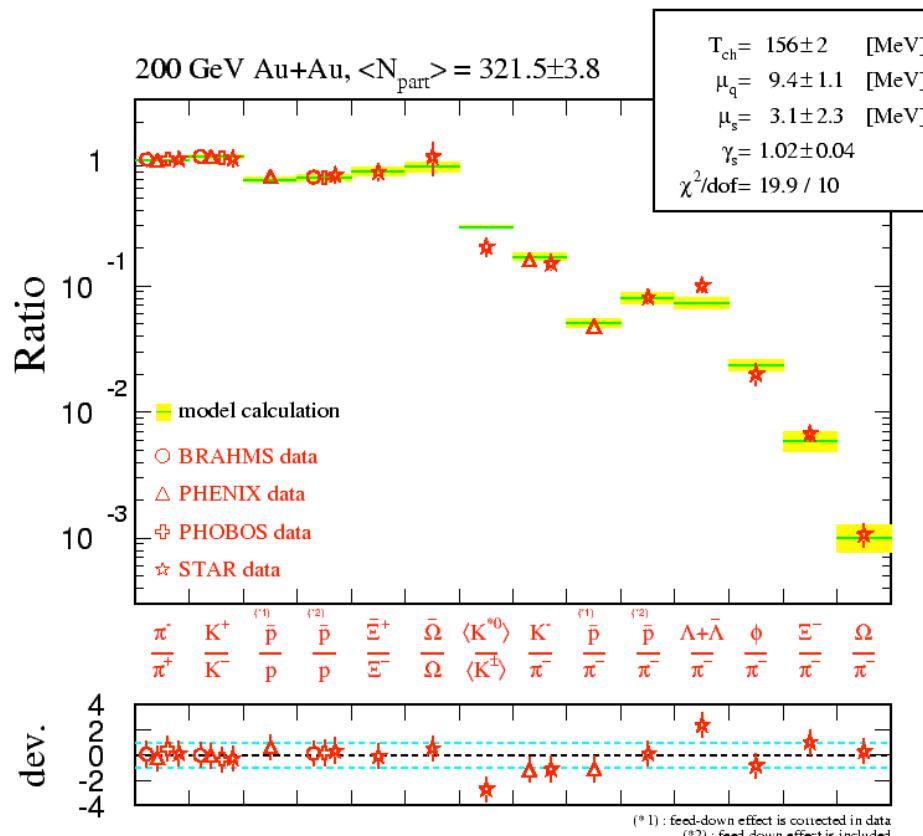
Hadron Spectra From RHIC

mid-rapidity, $p+p$ and $Au+Au$ collisions at 200 GeV





Hadron ratios and chemical fits



Au + Au at 200 GeV

(top 10% central collisions)

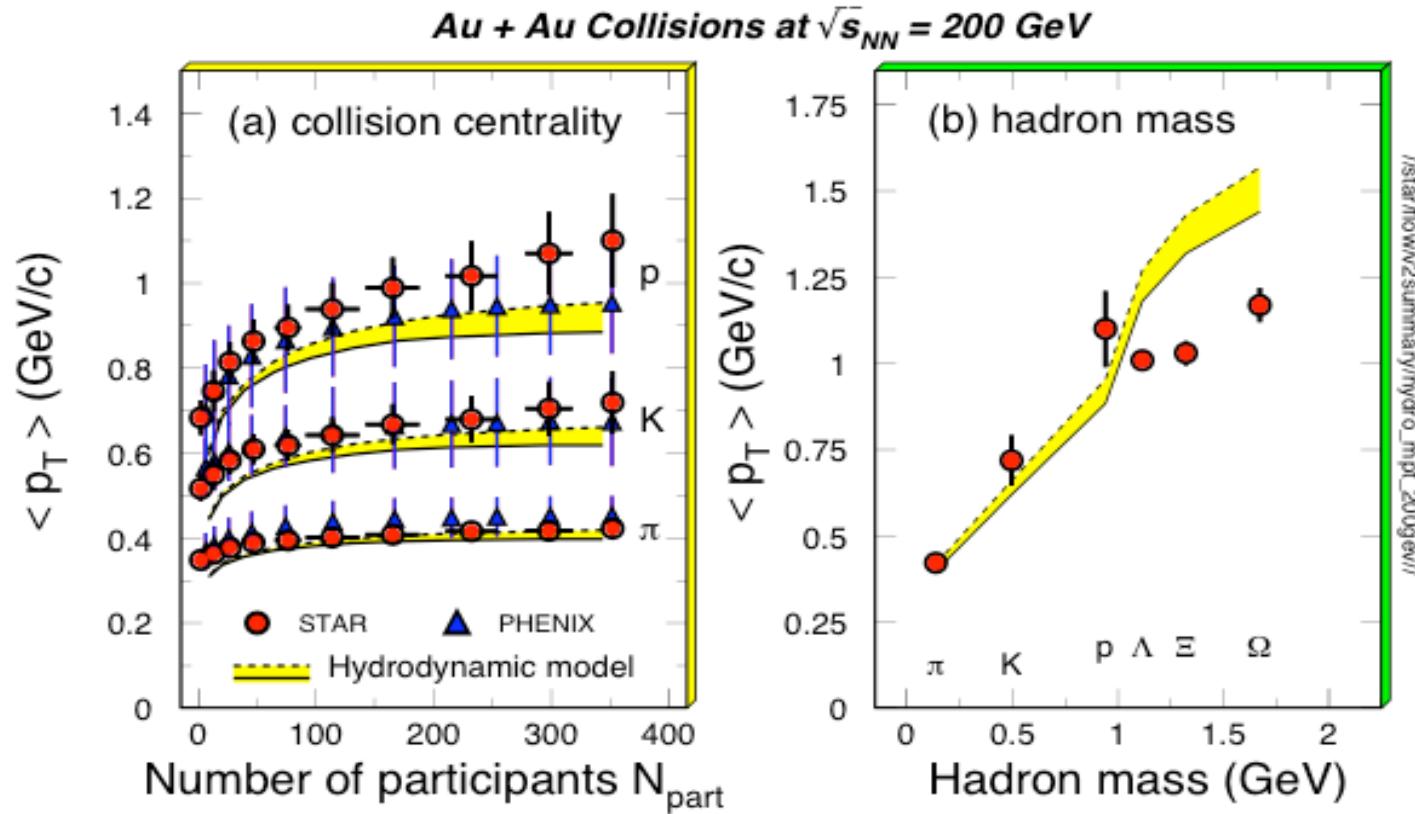
1) The model reproduce data within (almost) one sigma

2) Chemical freeze-out temperature

$$T_{\text{ch}} \sim 150-160 \text{ MeV}$$

3) Chemical fugacity \square_s is unity - chemical equilibrium between s-quark and light quarks. Only reached in central collisions at RHIC.

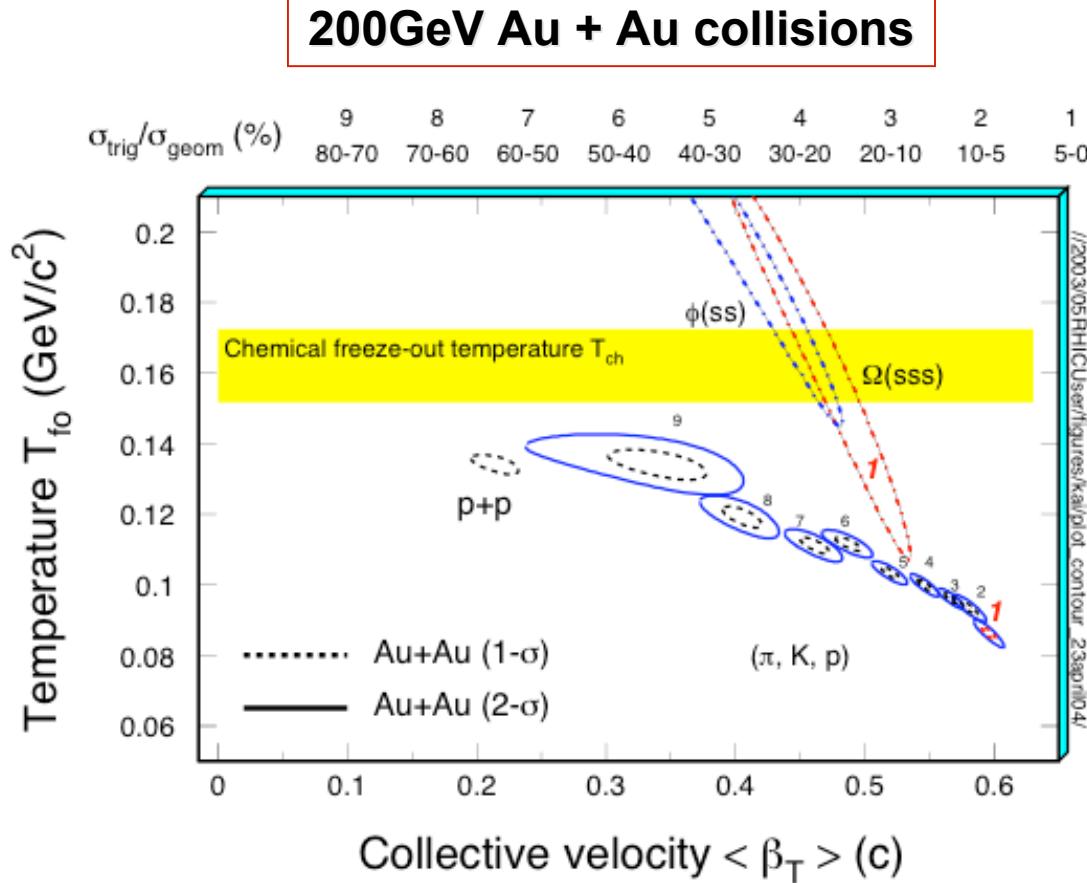
Compare with Model Results



Model results fit to π , K , p spectra well, but over predicted $\langle p_T \rangle$ for multi-strange hadrons - **Do they freeze-out earlier?**

Phys. Rev. C69 034909 (04); *Phys. Rev. Lett.* **92**, 112301(04); **92**, 182301(04); P. Kolb et al., *Phys. Rev. C67* 044903(03)

Thermal fits: T_{fo} vs. $\langle \bar{q} q \rangle$



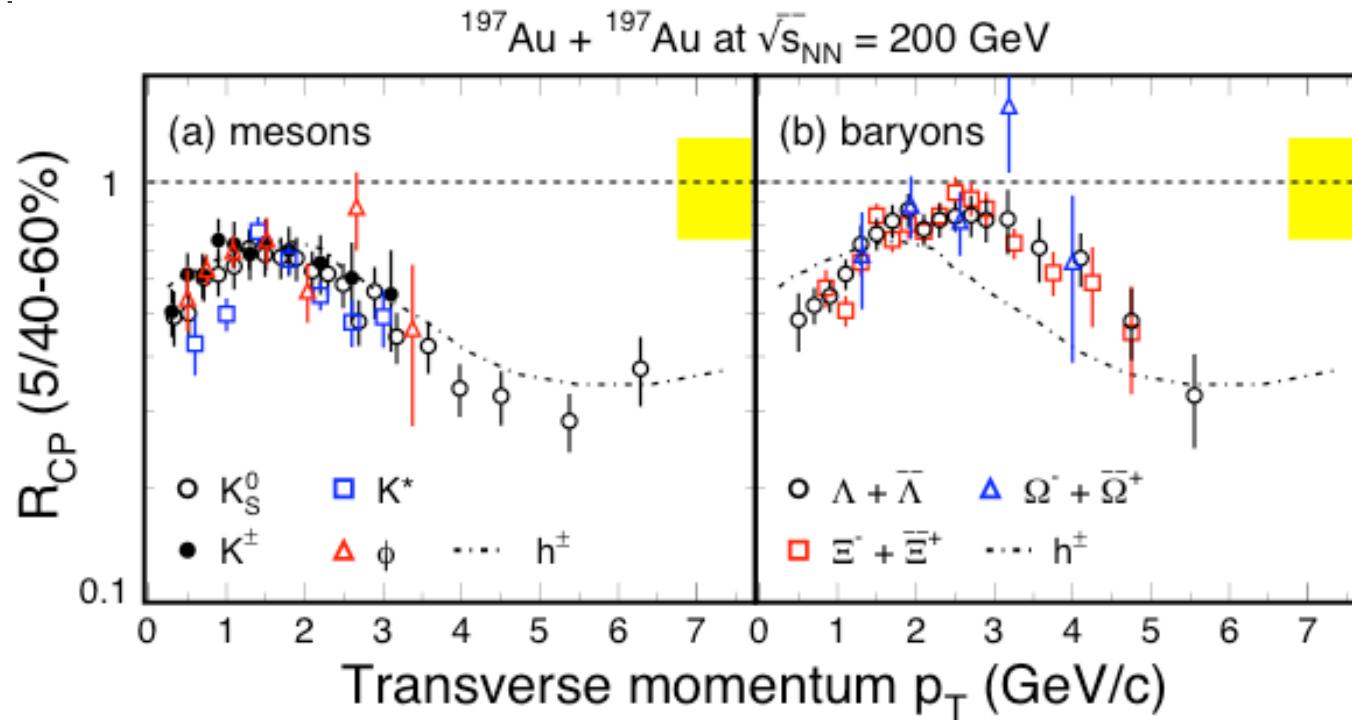
Chemical Freeze-out: inelastic interactions stop
Kinetic Freeze-out: elastic interactions stop

- 1) $\bar{q} q$, K , and p change smoothly from peripheral to central collisions.
- 2) At the most central collisions, $\langle \bar{q} q \rangle$ reaches 0.6c.
- 3) Multi-strange particles Ω , $\bar{\Lambda}$ are found at higher T_{fo} ($T \sim T_{ch}$) and lower $\langle \bar{q} q \rangle$

⇒ Sensitive to early partonic stage!
 ⇒ How about v_2 ?

STAR: NPA715, 458c(03); PRL 92, 112301(04); 92, 182301(04).

Nuclear Modification Factor



$$R_{CP}(p_T) = \frac{d^2 N^{central}}{d^2 N^{peripheral}} / \left(\frac{N^{central}}{N^{peripheral}} dp_T dy \right)$$

1) Baryon vs. meson effect!

2) Hadronization via coalescence

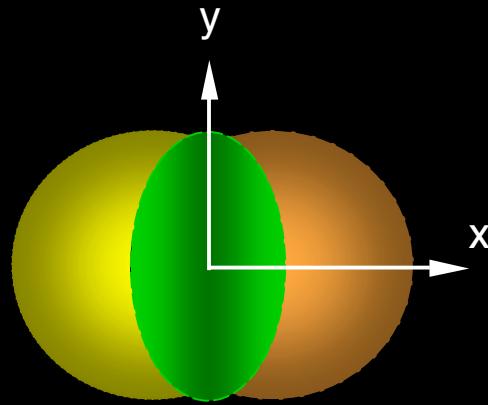
3) Parton thermalization (model)

- (K^0, \bar{K}) : *PRL* **92**, 052303(04); *NPA* **715**, 466c(03);
- *R. Fries et al, PRC* **68**, 044902(03)

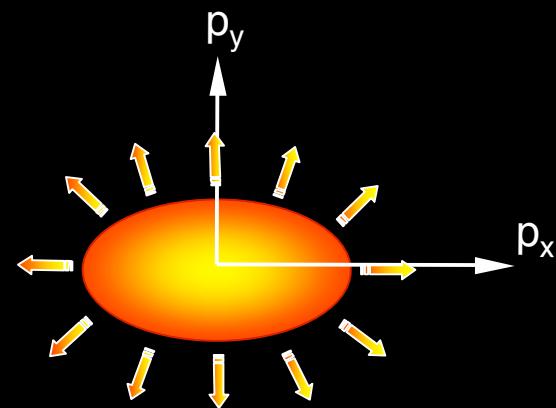


Anisotropy Parameter v_2

coordinate-space-anisotropy



momentum-space-anisotropy

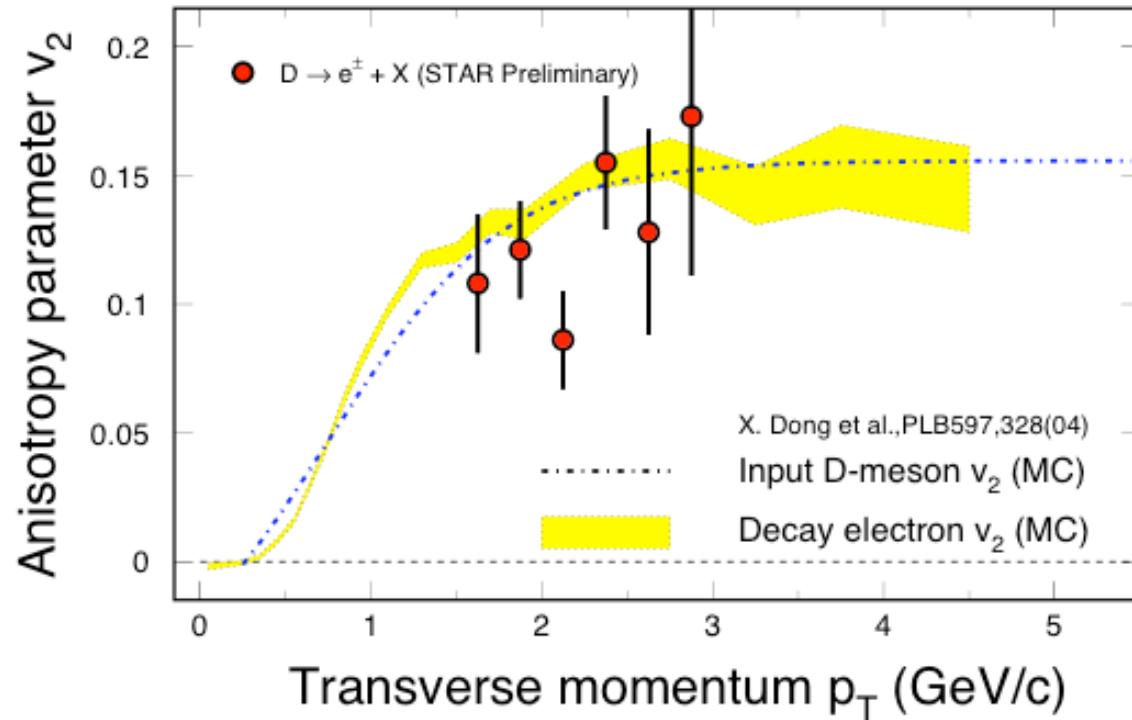


$$\square = \frac{y^2 - x^2}{y^2 + x^2}$$

$$v_2 = \langle \cos 2\square \rangle, \quad \square = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

Open charm v_2 - a comparison

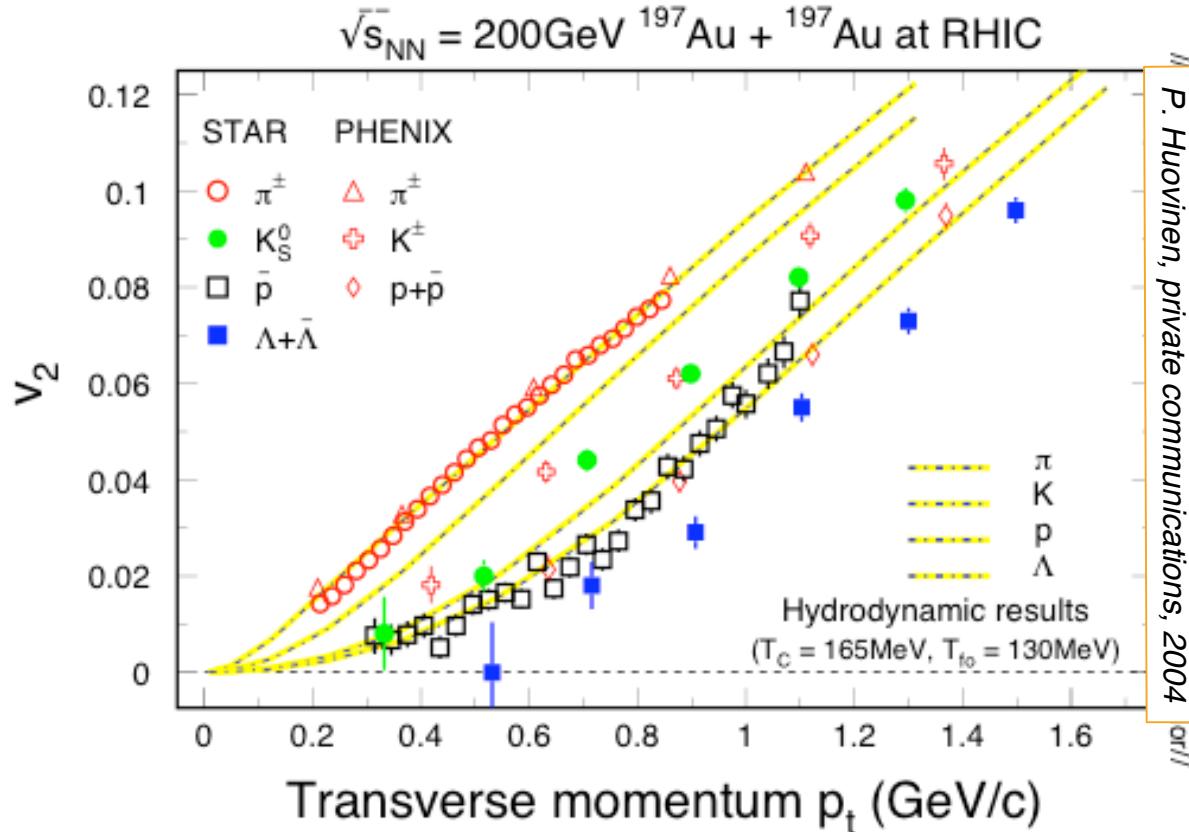


- 1) Constituent Quark Scaling for open charm hadron production?
- 2) Flow of charm-quark and the thermalization among light flavors?
- 3) ...????

Preliminary Data: F. Laue, SQM04

MC: X. Dong, S. Esumi, P. Sorensen, N. Xu and Z. Xu, Phys. Lett. **B597**, 328(2004).

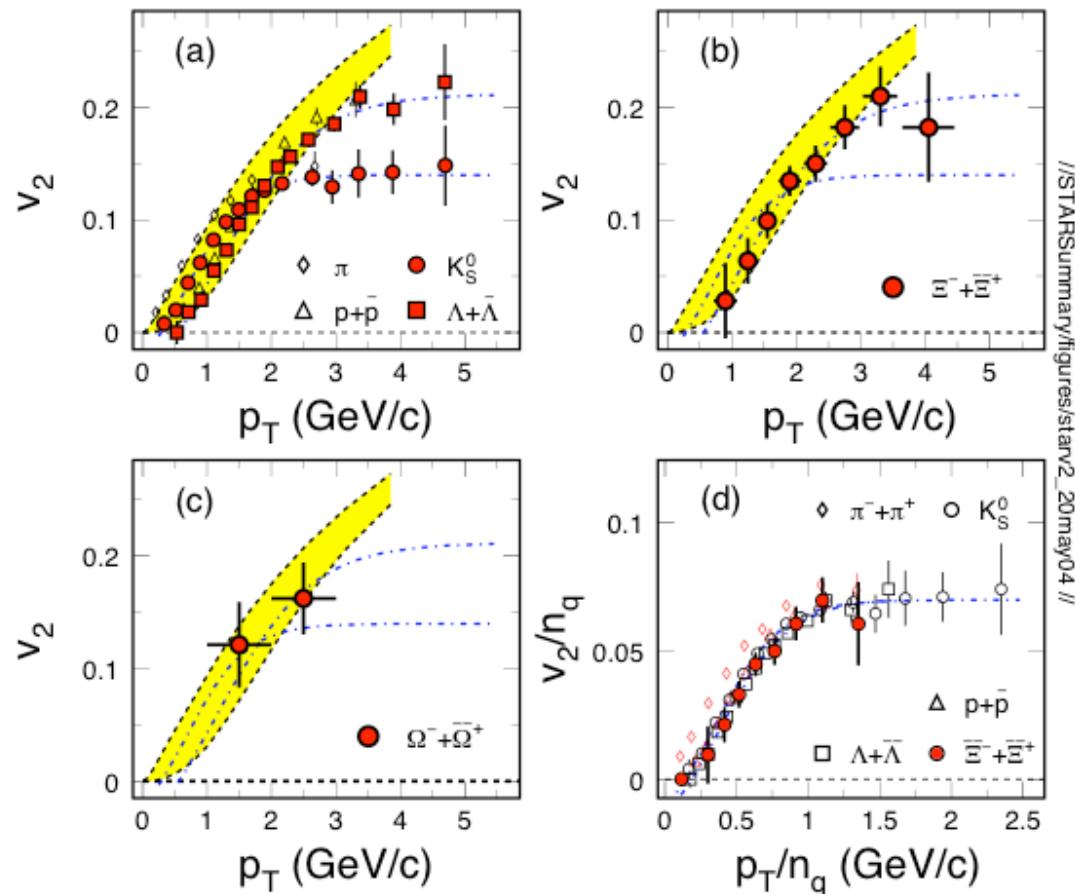
v_2 at low p_T region



- At low p_T , hydrodynamic model seem to fit for minimum bias events, especially the mass hierarchy.
- More theory work needed to understand details such as v_2 centrality dependence, consistency with hadron spectra.



v_2 at all p_T measured region



The v_2 , the spectra of multi-strange hadrons, and the scaling of the number of constituent quarks

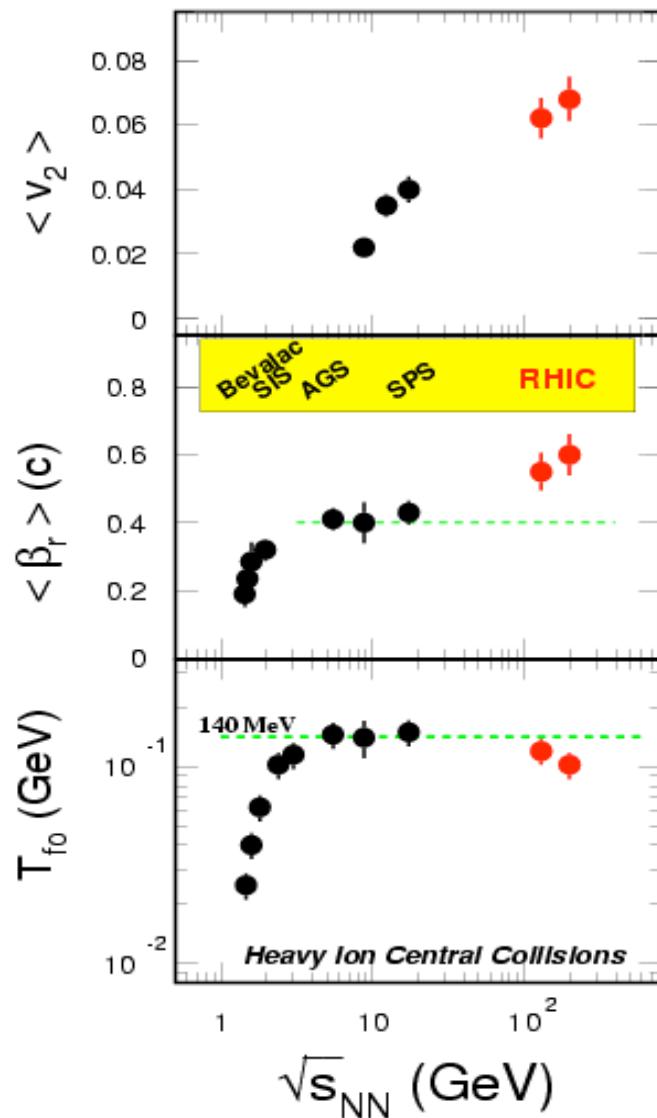
- ⇒ Partonic collectivity has been attained at RHIC!
- ⇒ Deconfinement, model dependently, has been attained at RHIC!

Next question is the thermalization of light flavors at RHIC:

- v_2 of charm hadrons
- J/ψ distributions !!

PHENIX: PRL91, 182301(03) **STAR**: PRL92, 052302(04)
Models: R. Fries et al, PRC68, 044902(03), Hwa, nucl-th/0406072

Bulk Freeze-out Systematics



The additional increase in $\langle v_2 \rangle$ is likely due to partonic pressure at RHIC.

- 1) v_2 self-quenching, hydrodynamic model works at low p_T
- 2) Multi-strange hadron freeze-out earlier, $T_{fo} \sim T_{ch}$
- 3) Multi-strange hadron show strong v_2



Summary & Outlook

- (1) Charged multiplicity - high initial density
 - (2) Parton energy loss - ***QCD*** at work
 - (3) Collectivity - pressure gradient ∂P_{QCD}
- ⇒ **Deconfinement and Partonic collectivity**

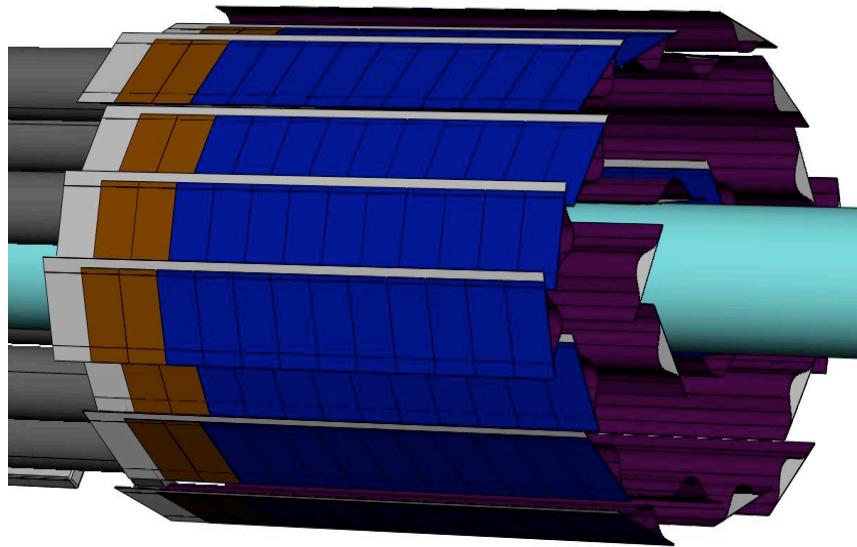
Open issues - partonic (***u,d,s***) thermalization

- heavy flavor v_2 and spectra
- di-lepton and thermal photon spectra



Upgrades at STAR

STAR MRPC - TOF



STAR MicroVertex Tracker

Active pixel sensors (APS)
Two layers of thin silicon

- Full open charm measurements
- Full resonance measurements with both hadron and lepton decays



Open Issues

1) Nuclear stopping/baryon transport:

- topological junction, a la Gyulassy
- nucleon structure function, a la Muller

2)* Thermalization and QGP temperature:

3)* Hadronization via coalescence/recombination:

- p+p collisions?
- low p_T pions? Where are gluons? Heavy flavor?

4) Chiral symmetry restoration:

Details for QGP discovery!

